UNIVERSITY OF ALBERTA

# Inter-Procedural Analysis

CMPUT 416/500
Foundations of Program Analysis

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## Previously

- Points-to
- Aliases
- Must and May analyses
- Incomplete Programs
- Weak vs Strong Updates
- Access Paths
- Distributivity

## Inter-Procedural Data-Flow Analysis

- Beyond procedure boundaries
- Model the effects of
  - calls in the callers, and
  - calling contexts in the callees

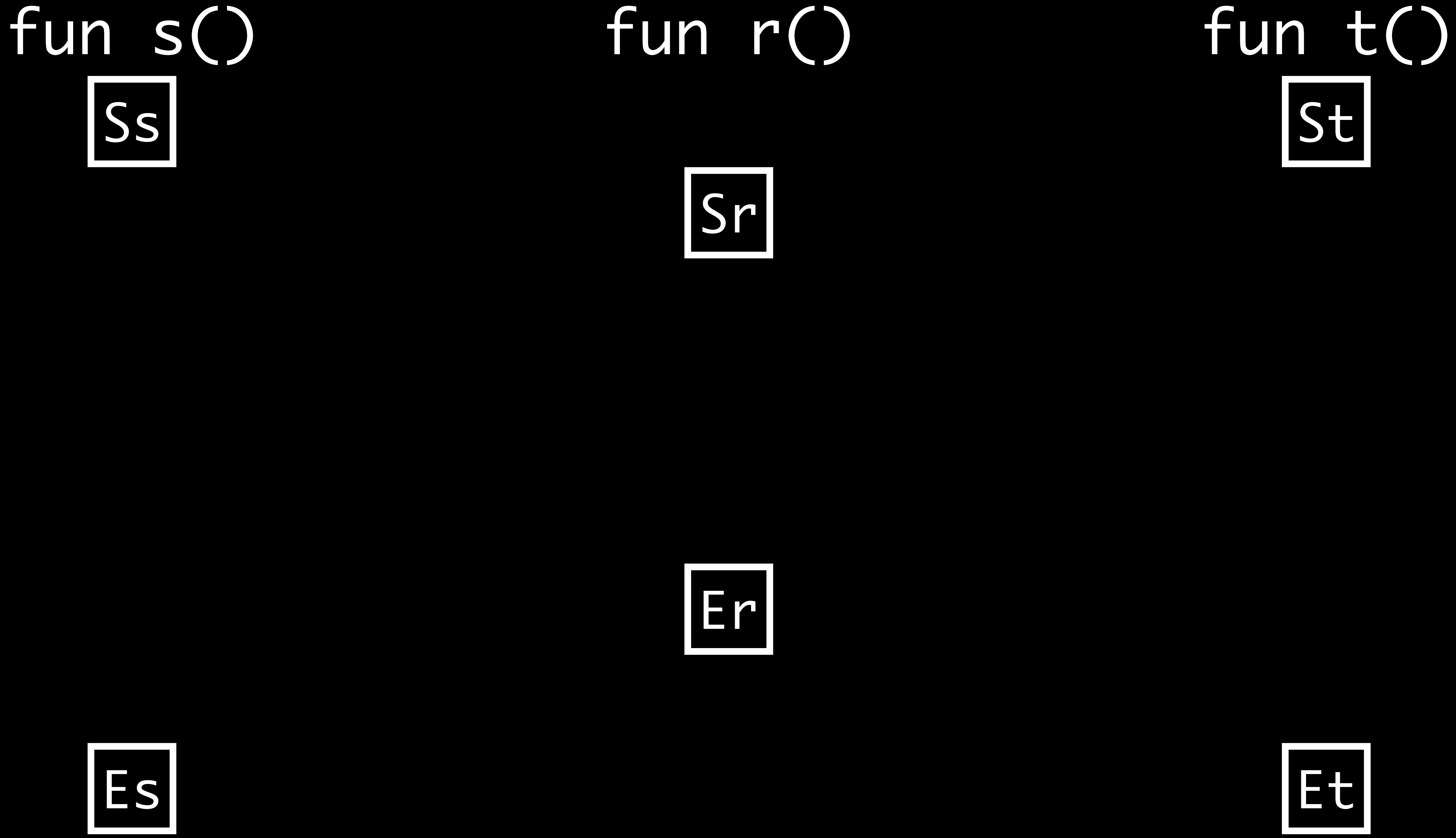
## Inter-Procedural Data-Flow Analysis

- Approaches
  - Generic: Call-strings approach, functional approach
  - Problem specific:  Alias analysis,
    Points-to analysis,
    Partial redundancy elimination,
    Constant propagation

## Inter-Procedural Data-Flow Analysis

```
fun s()          fun r()          fun t()
```

## Inter-Procedural Data-Flow Analysis



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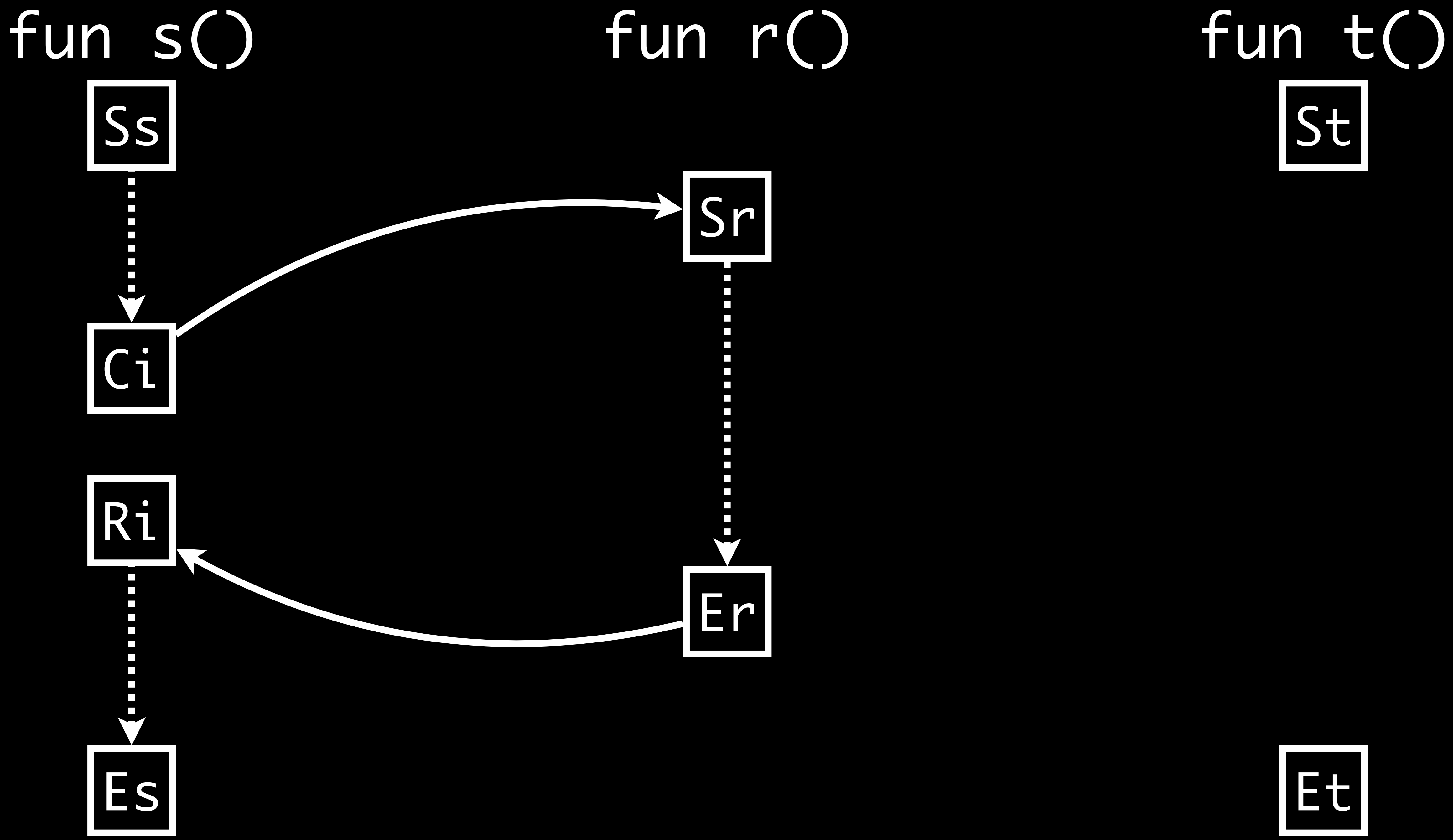

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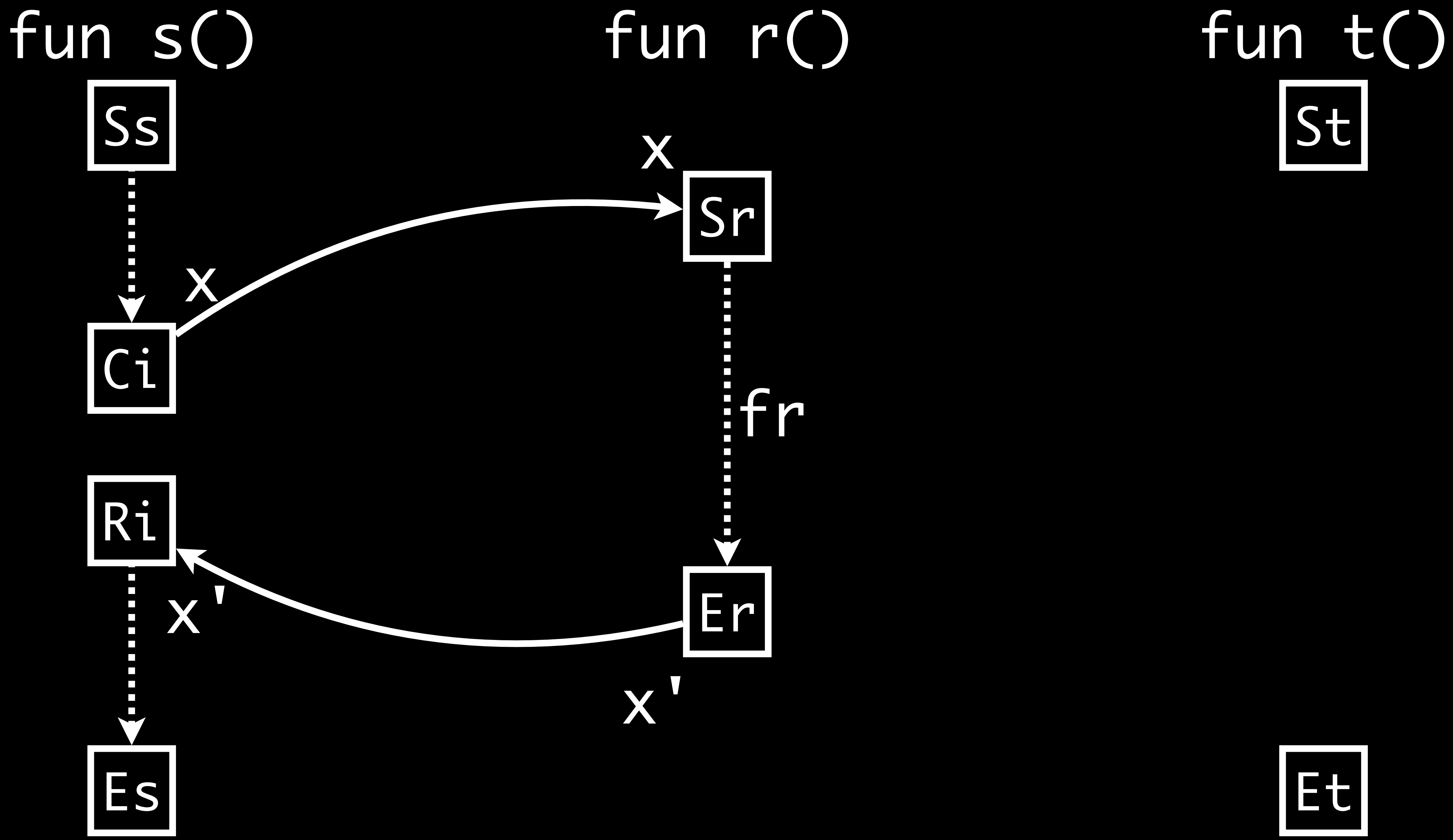

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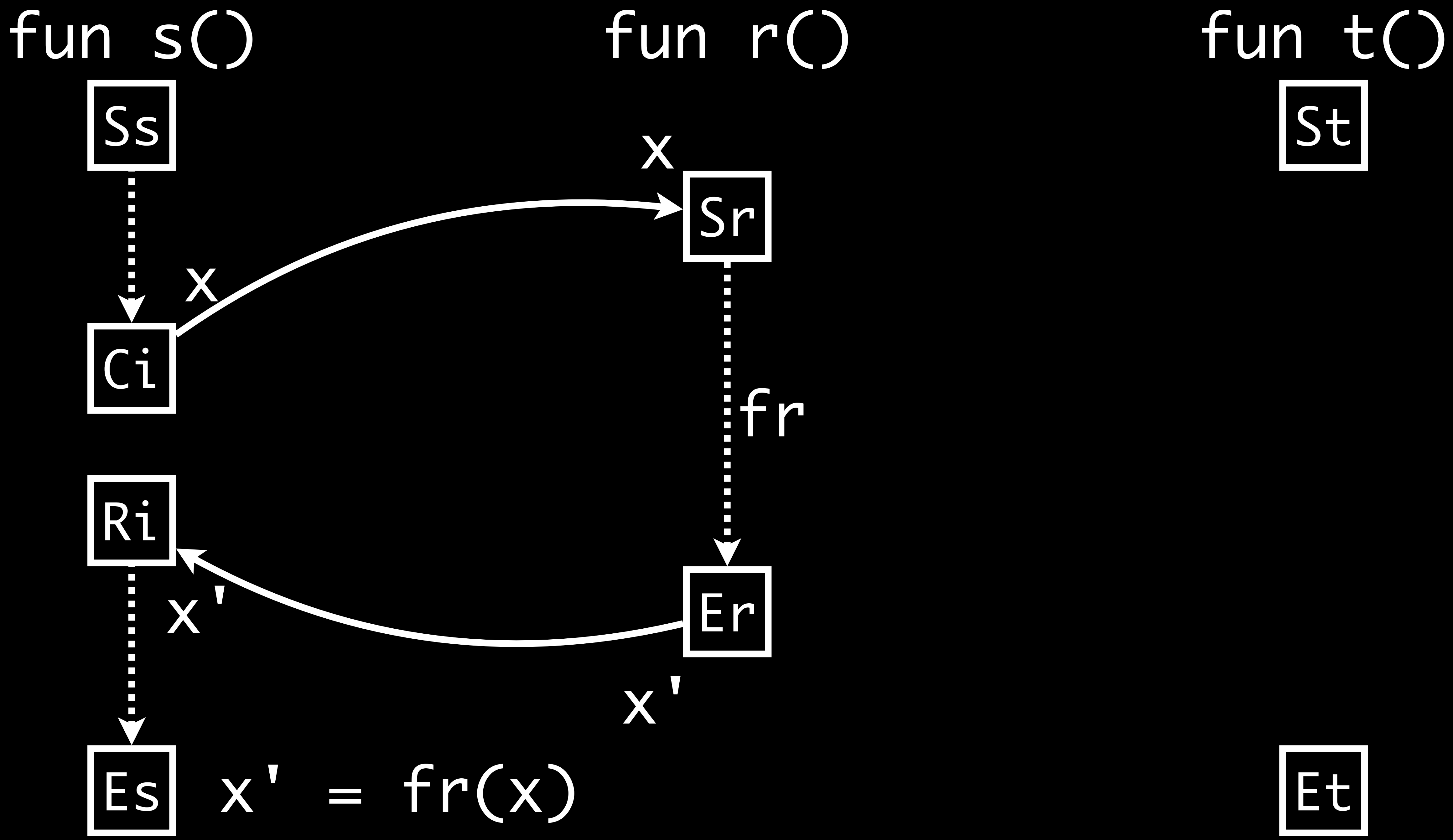

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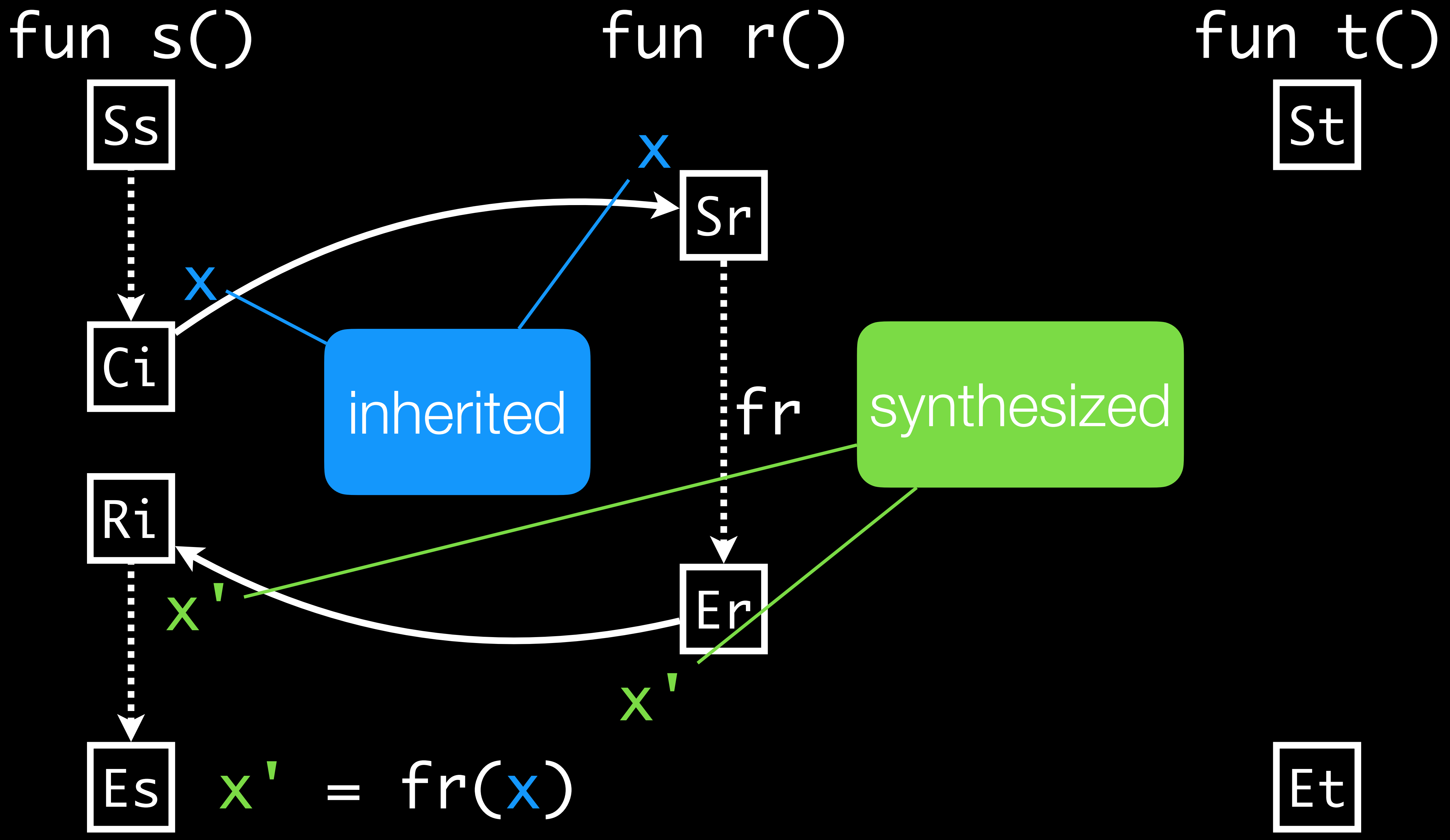

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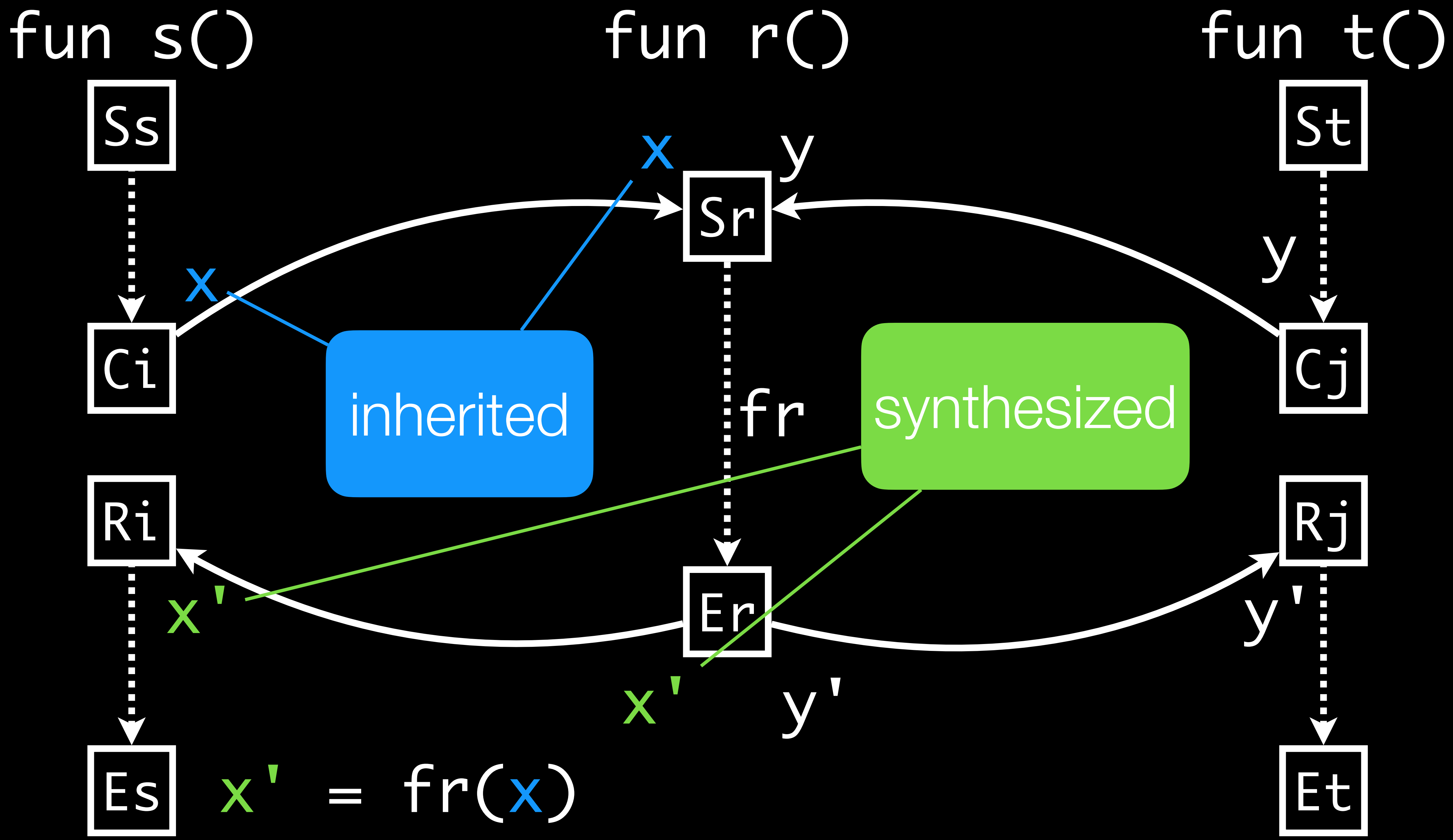

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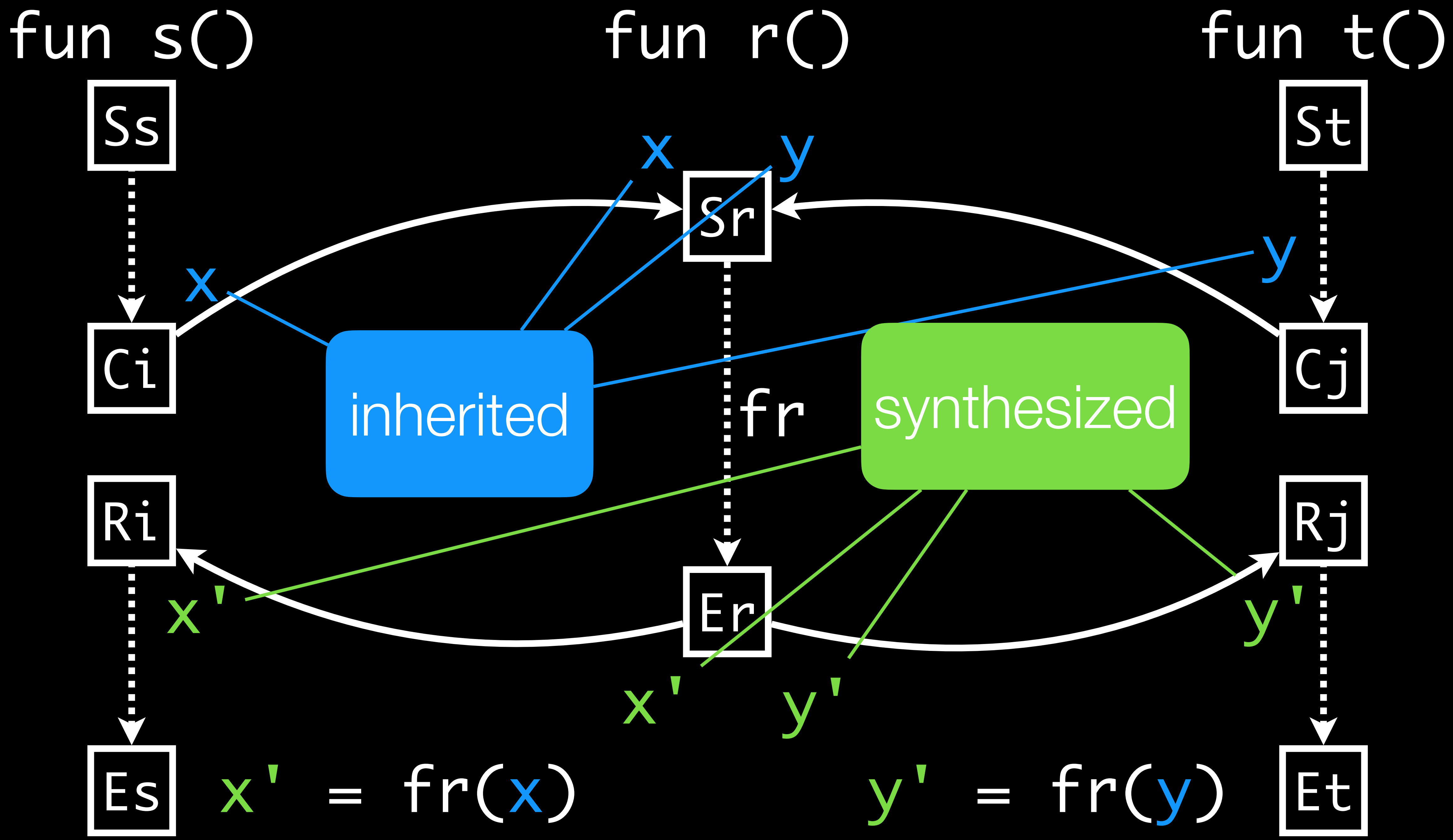


## Inherited vs Synthesized Analysis Information

## Inherited Analysis Information

- Answering questions about formal parameters and global variables:
  - Which variables carry constant values?
  - Which variables aliased with eac[illegible] o[illegible]her?
  - Which locations can a pointe[illegible] point to?

May
or
Must

## Synthesized Analysis Information

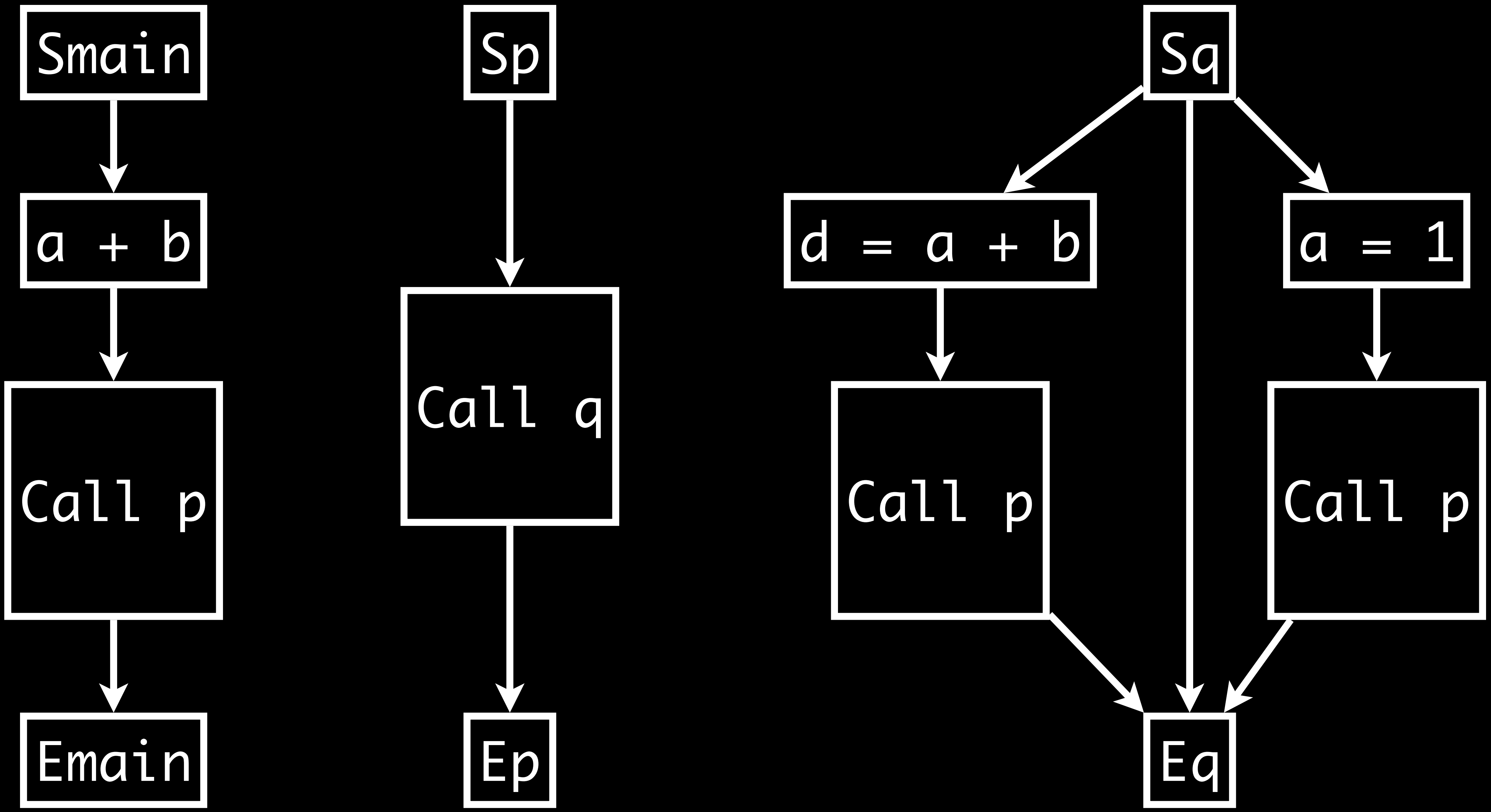
- Answering questions about side-effects of a procedure call:
  - Which local/global/formal variables are defined in a callee?
  - Which local/global/form variables are used by a callee?

May
or
Must

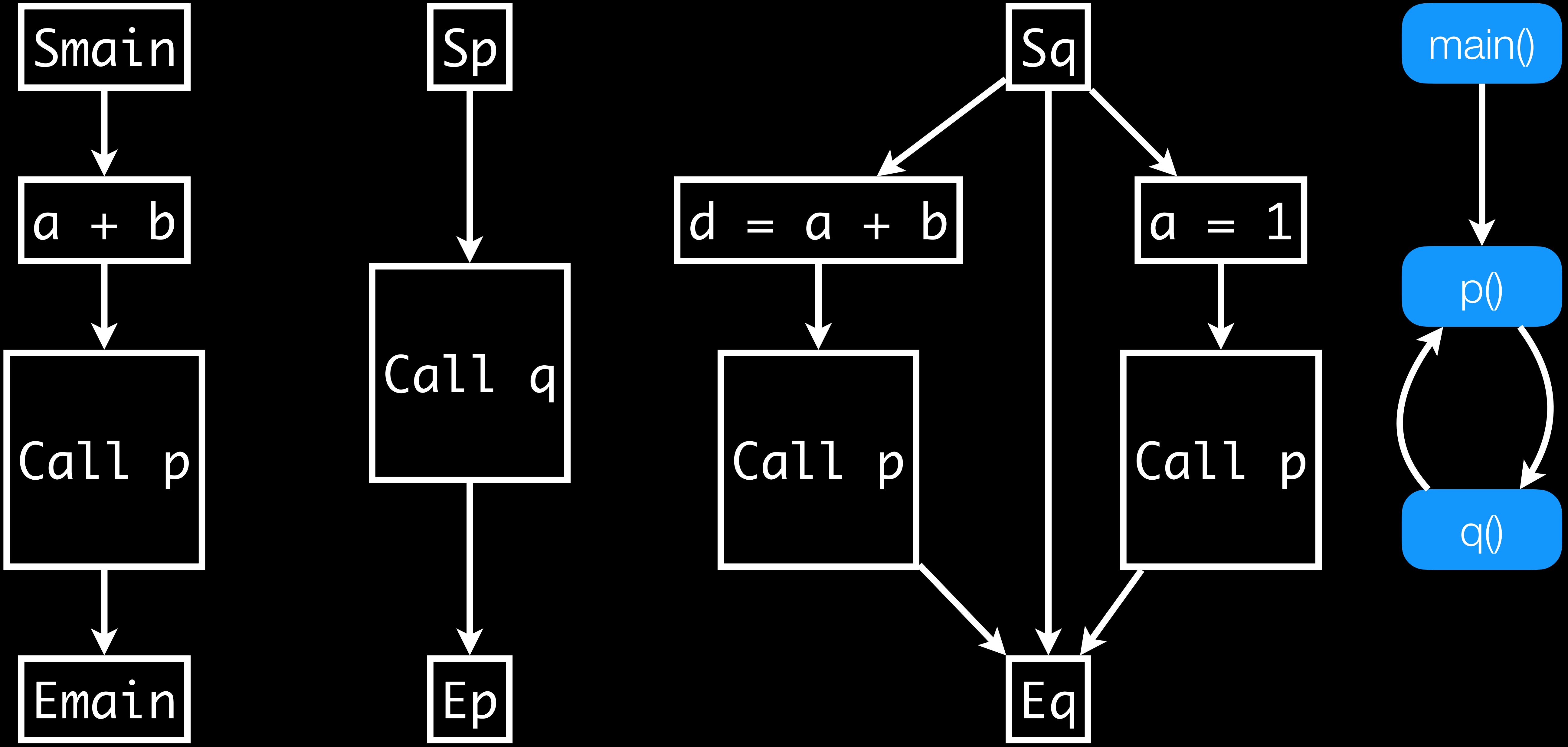
## Inter-Procedural Control-Flow Graph (ICFG)

aka “program super-graph”

# Procedure Space

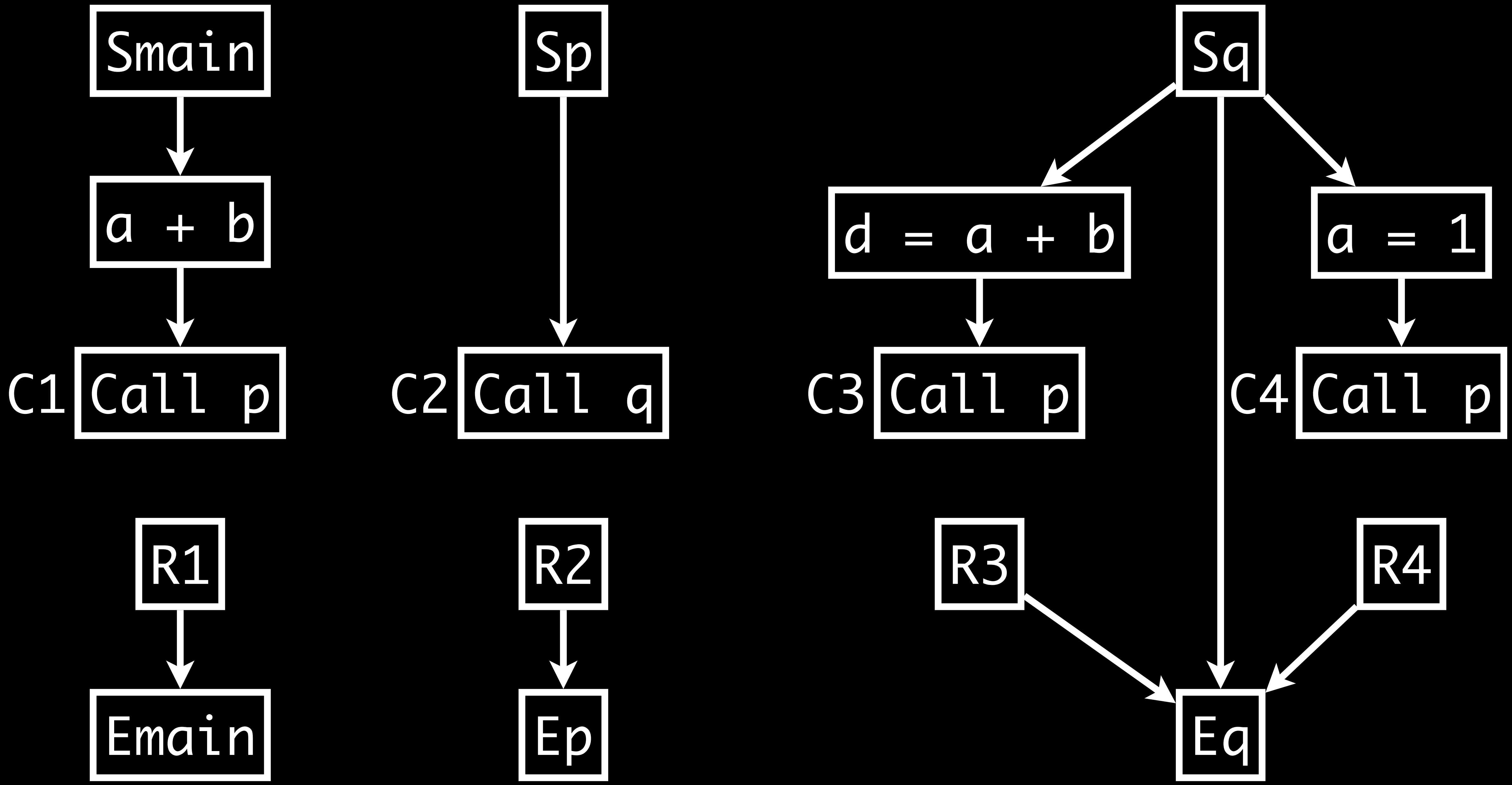


## Call Graph

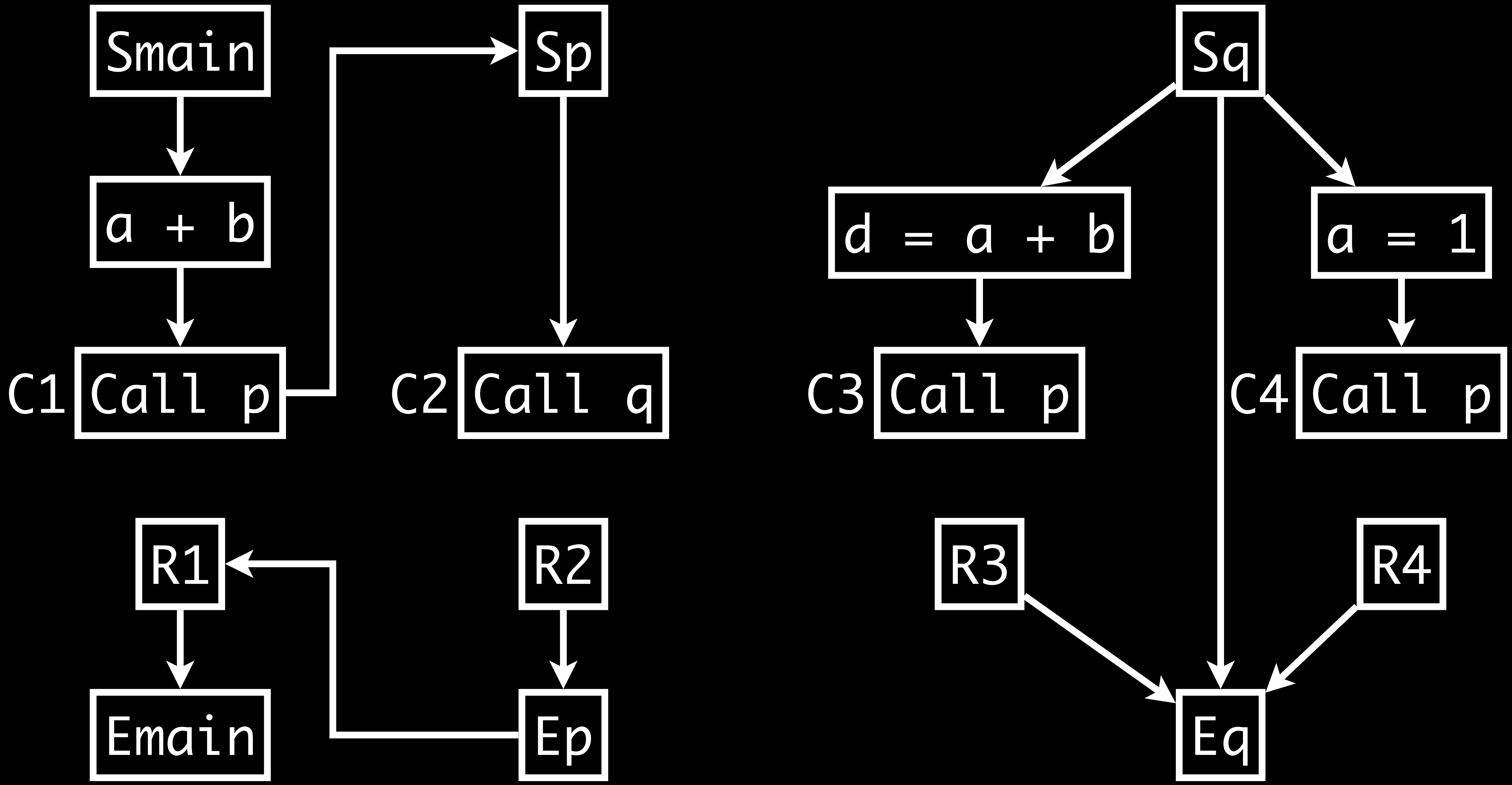


Smain
a + b
Call p
Emain
Sp
Call q
Ep
Sq
d = a + b
Call p
a = 1
Call p
Eq
main()
p()
q()

## Introduce Return Sites



# Caller-Callee Relationships



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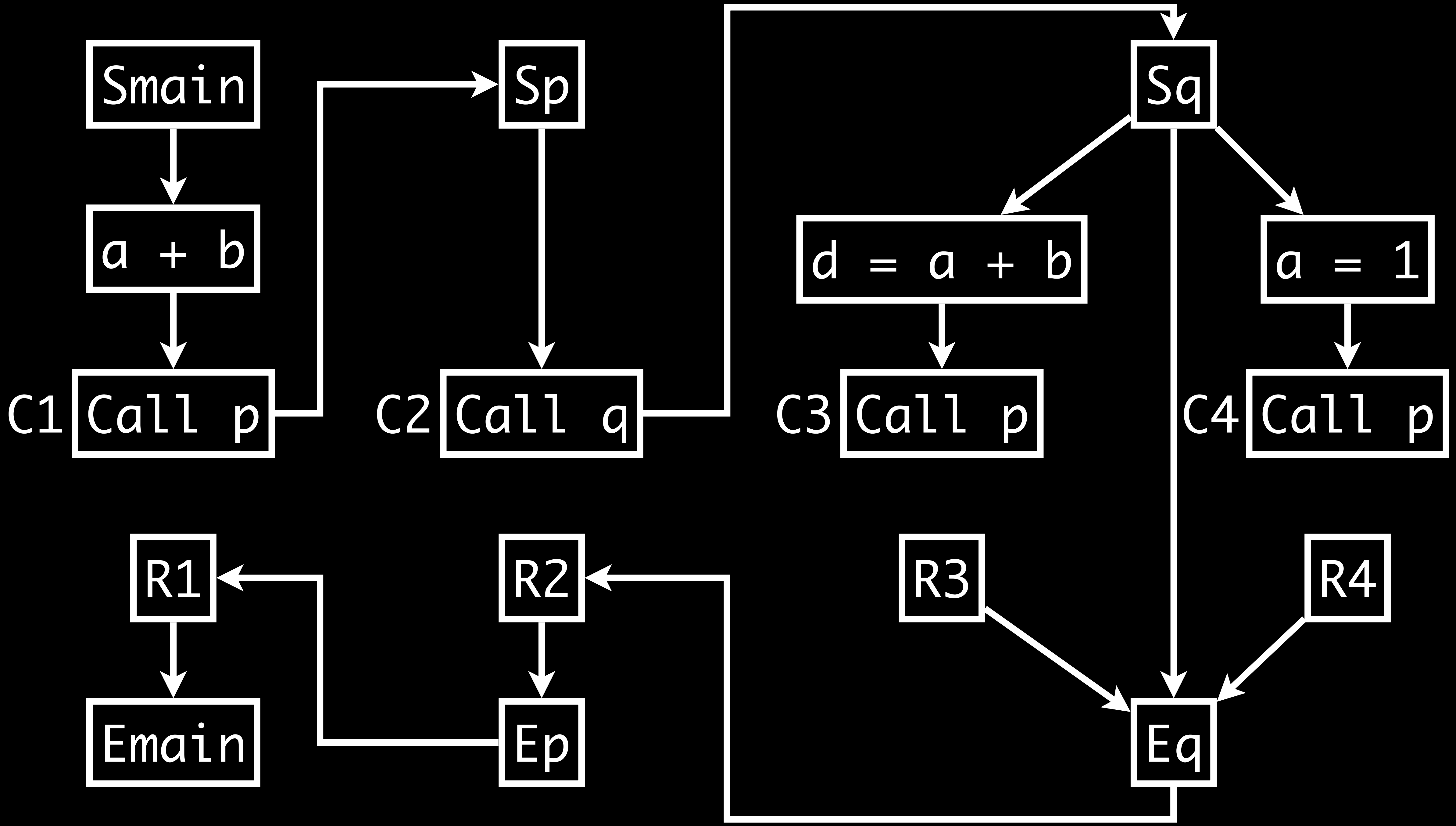

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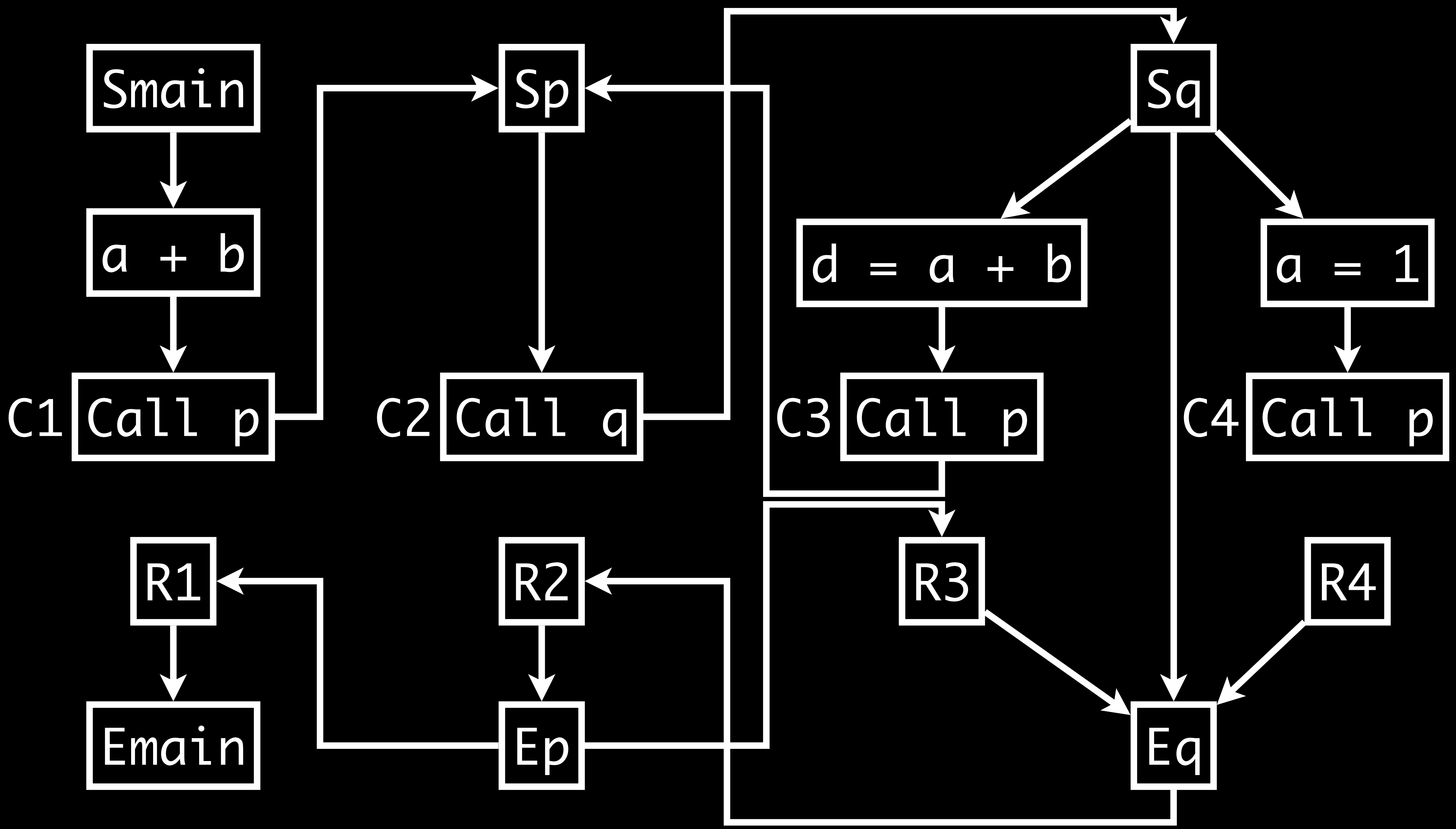

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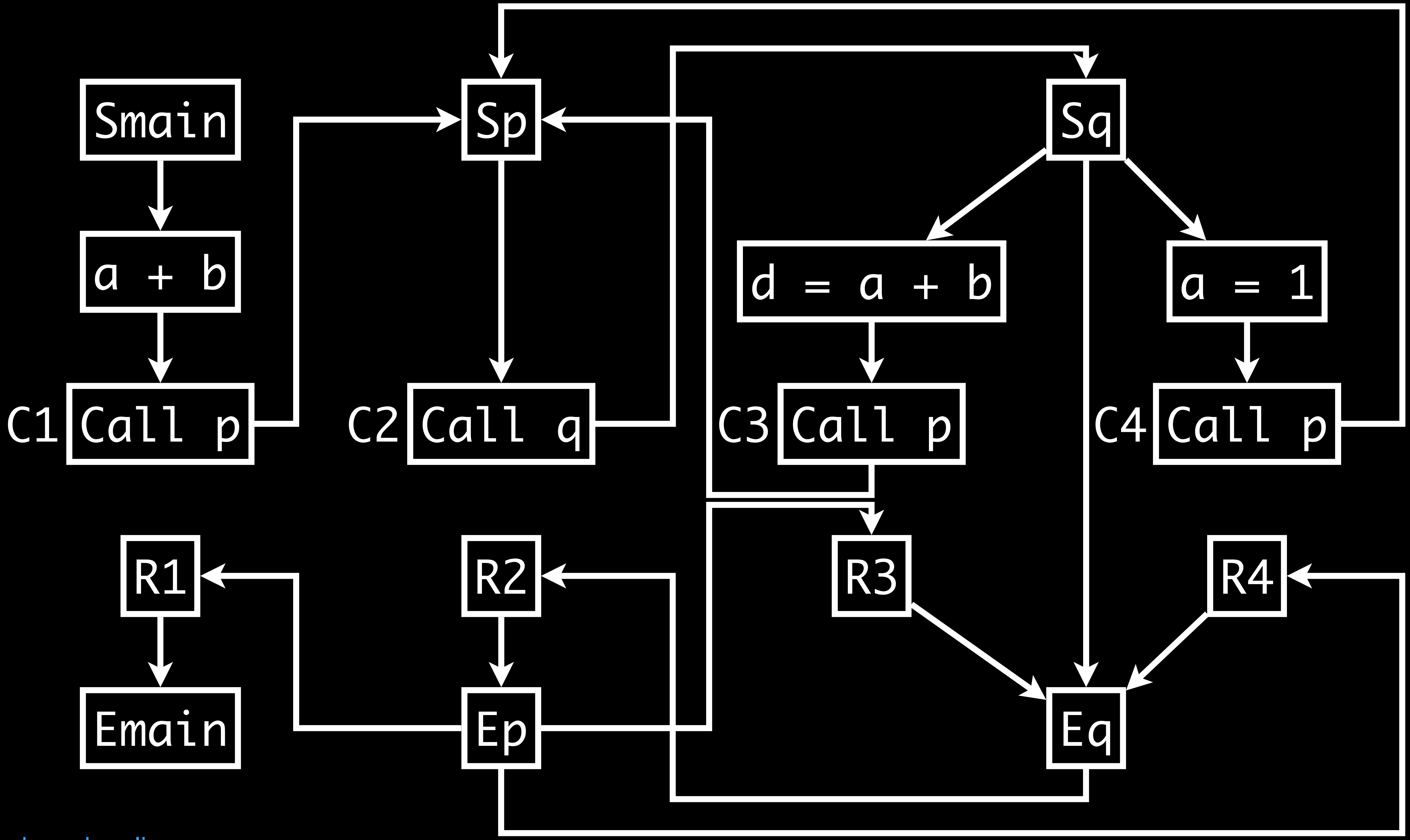
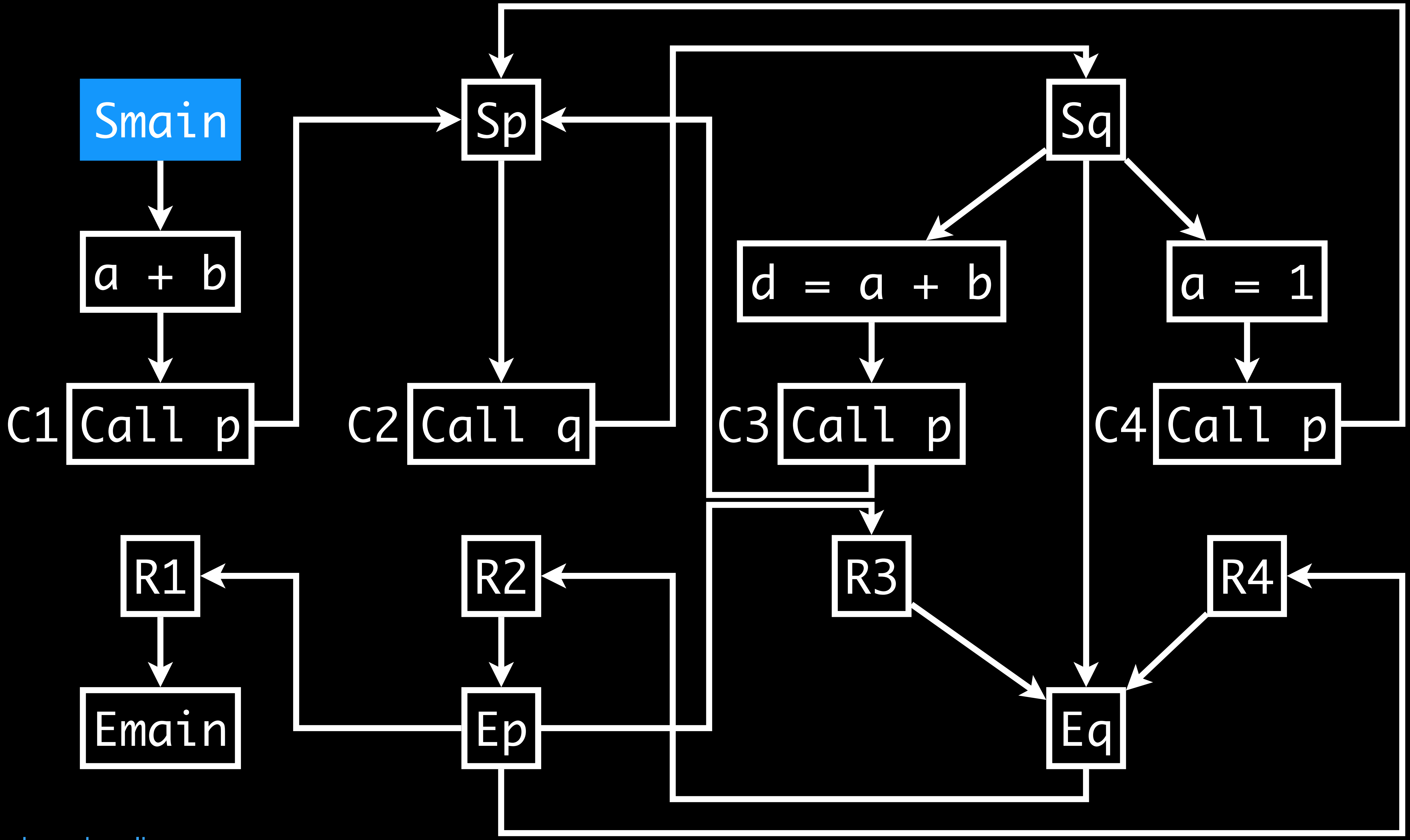


## Valid/Realizable Path



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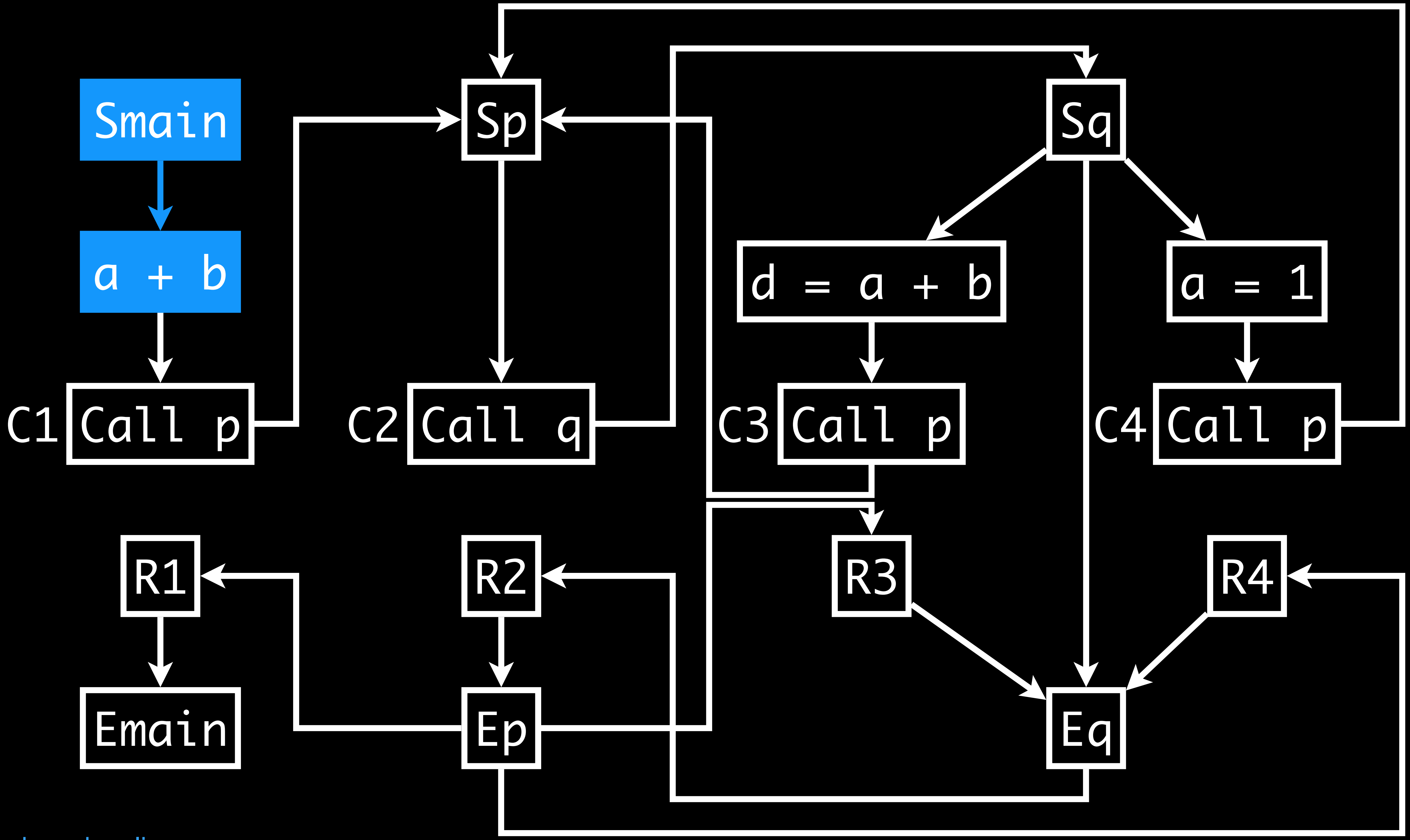

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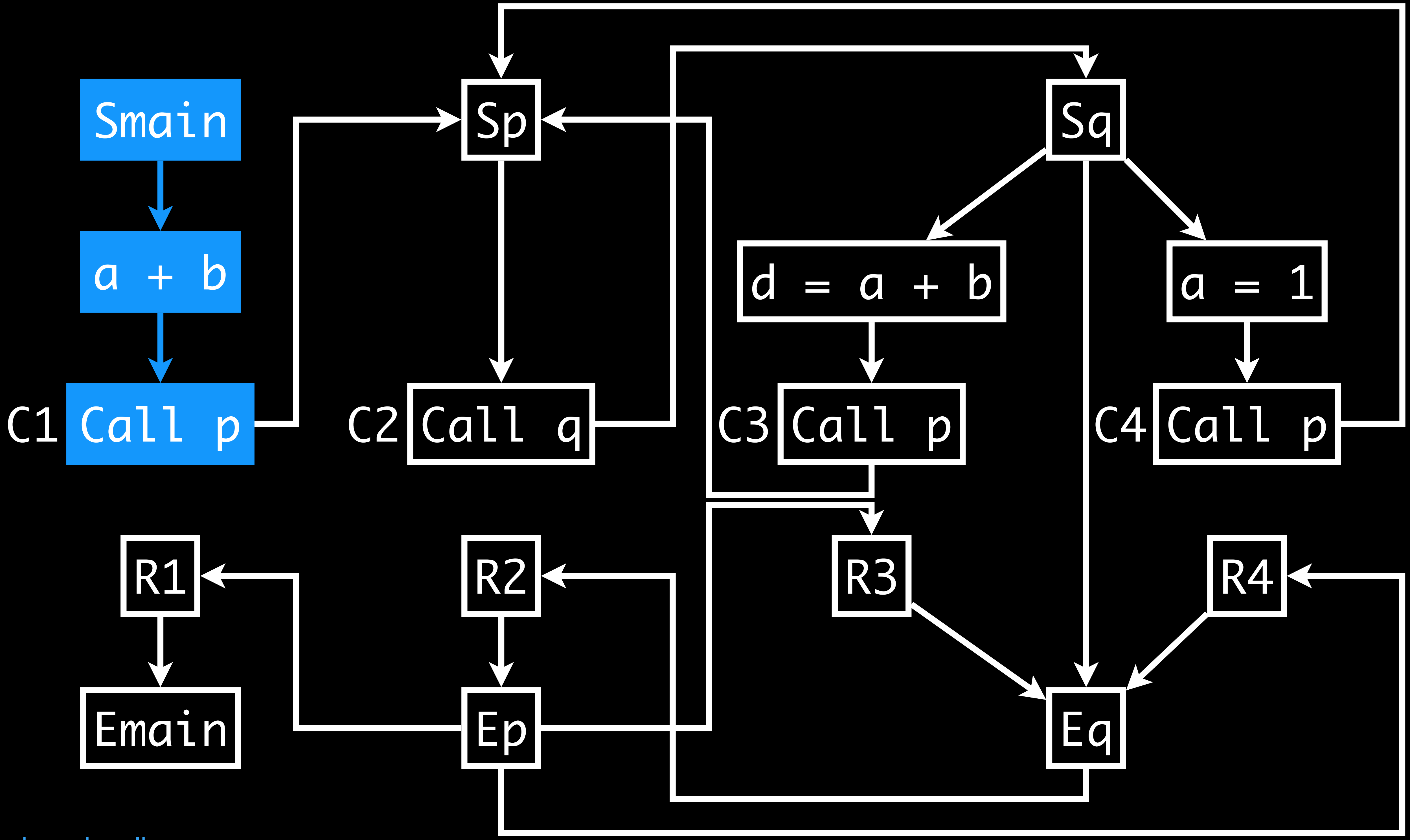

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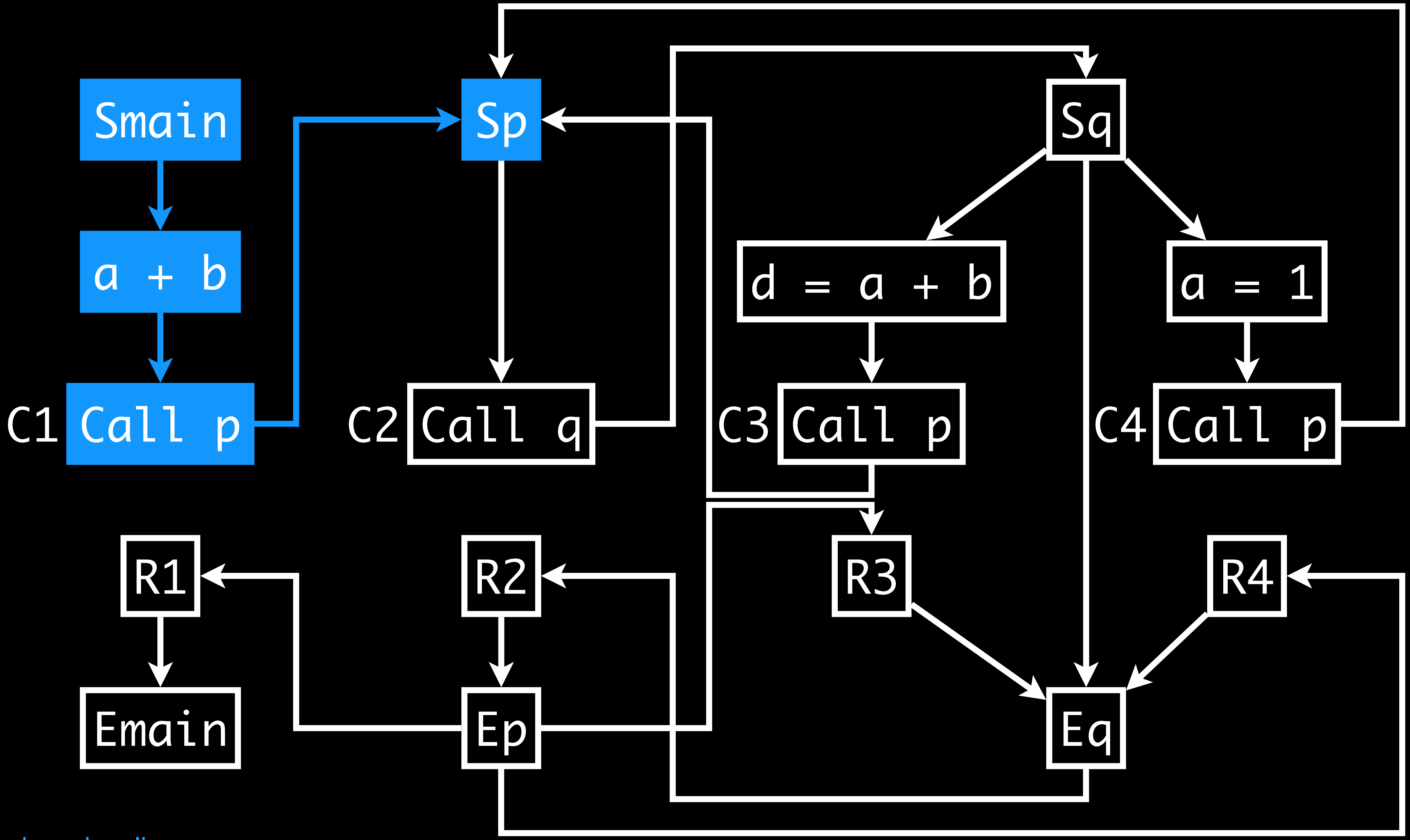

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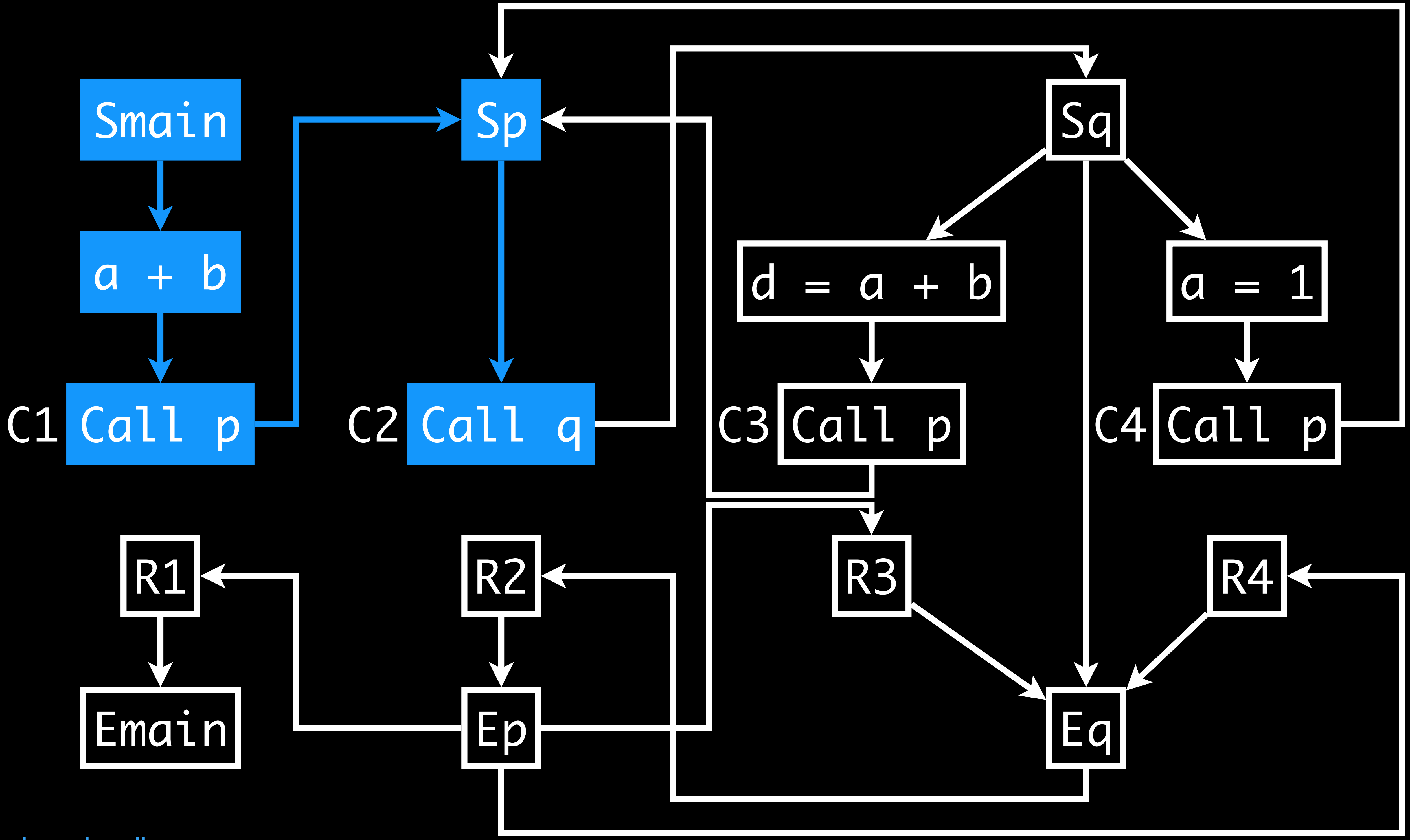

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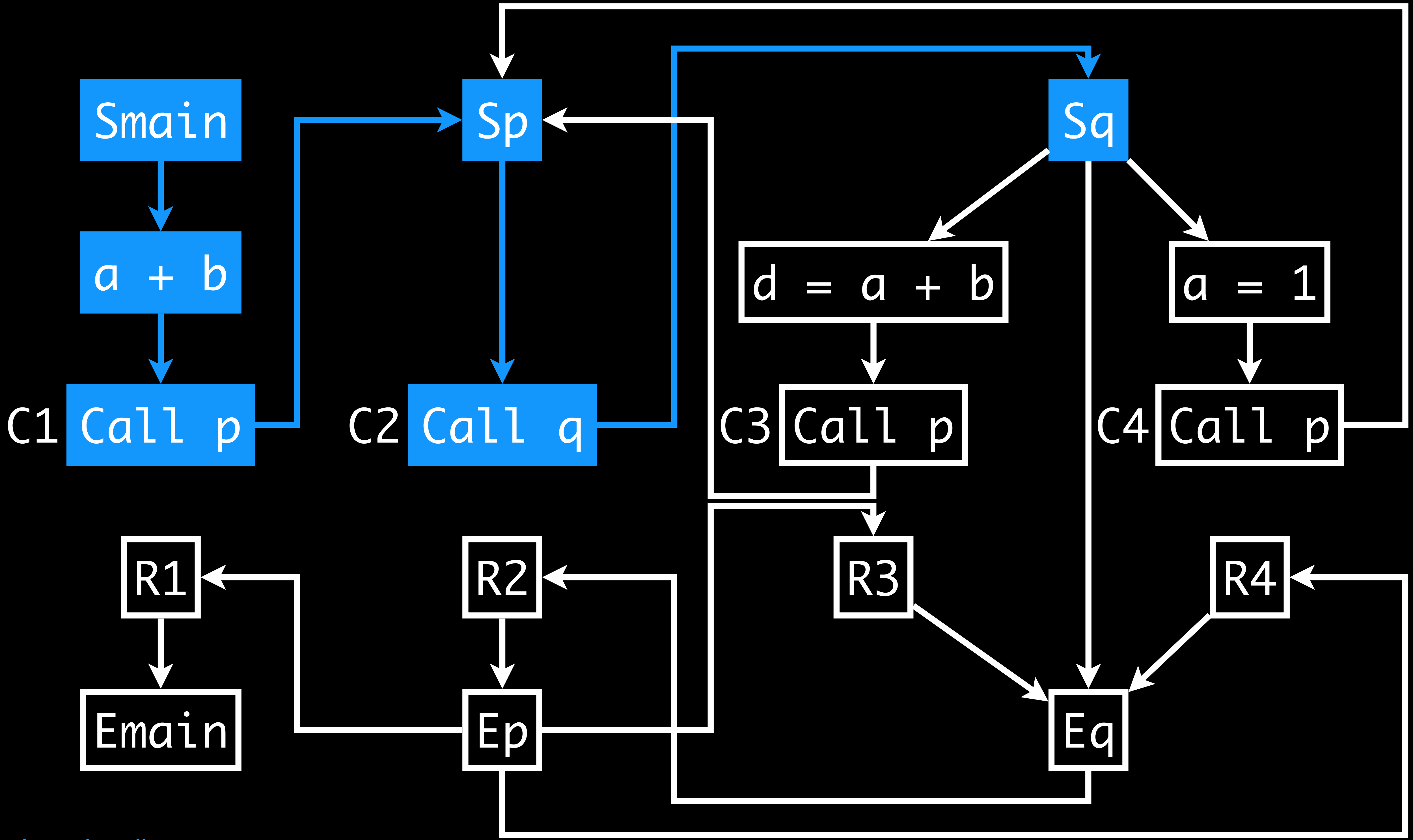

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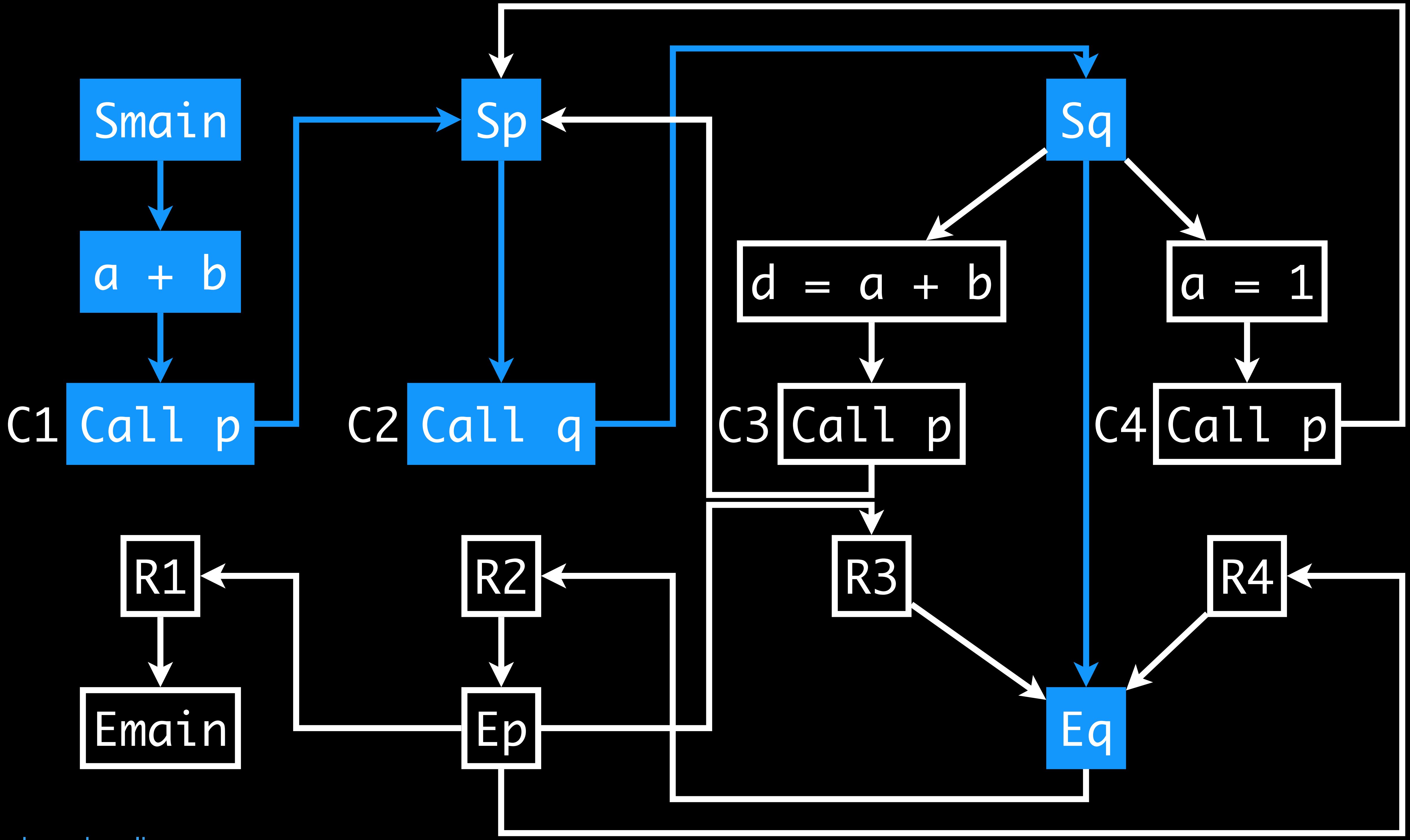

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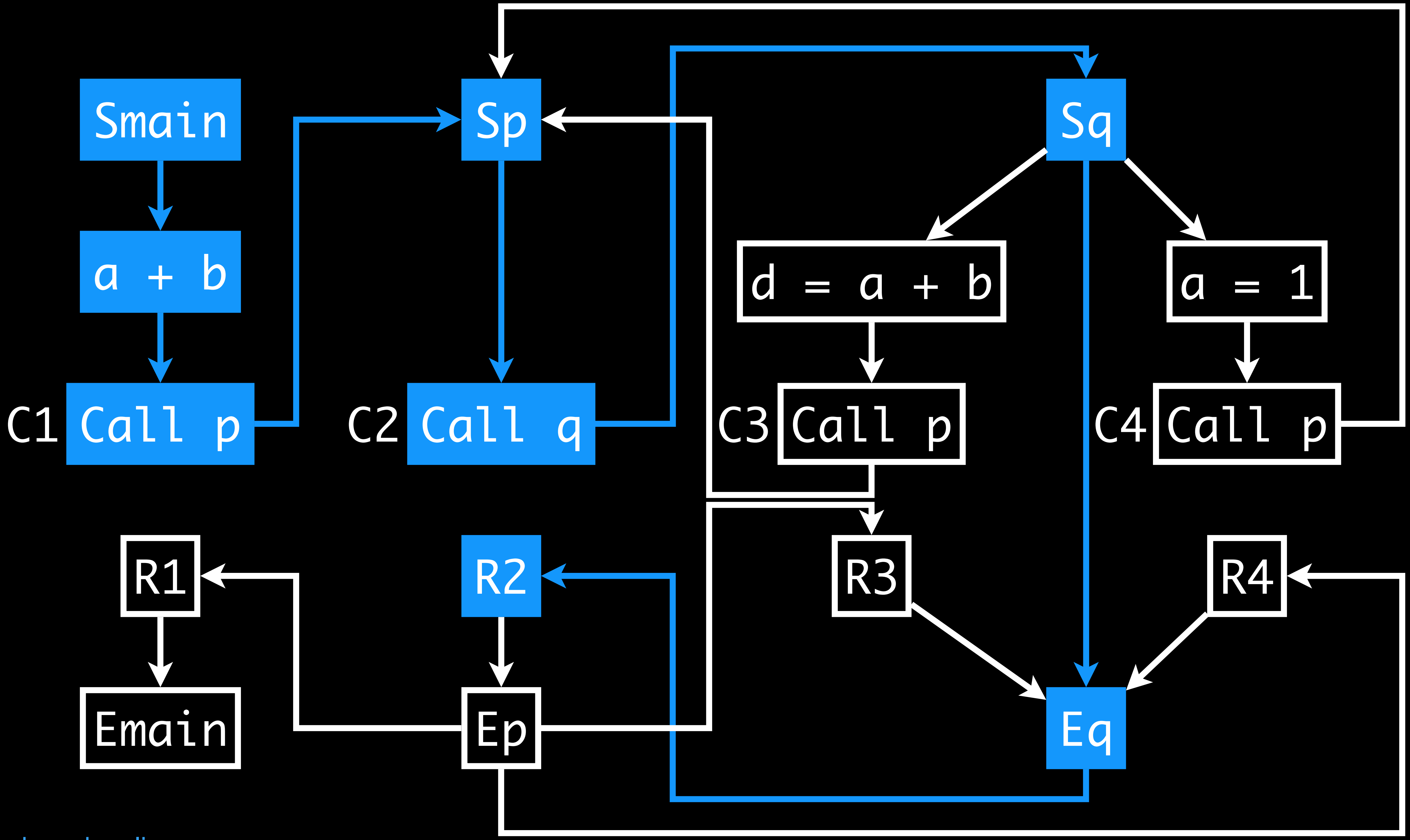

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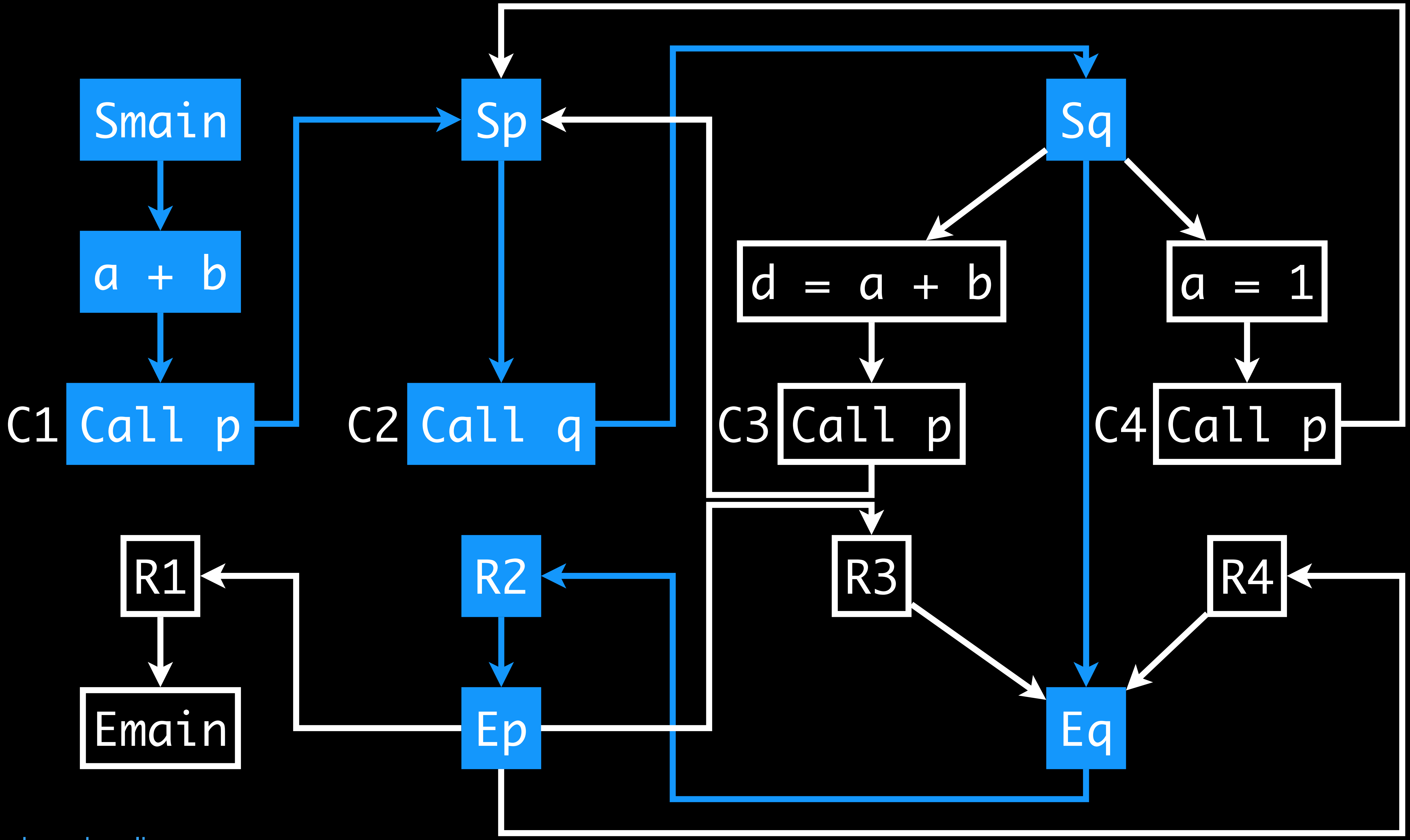

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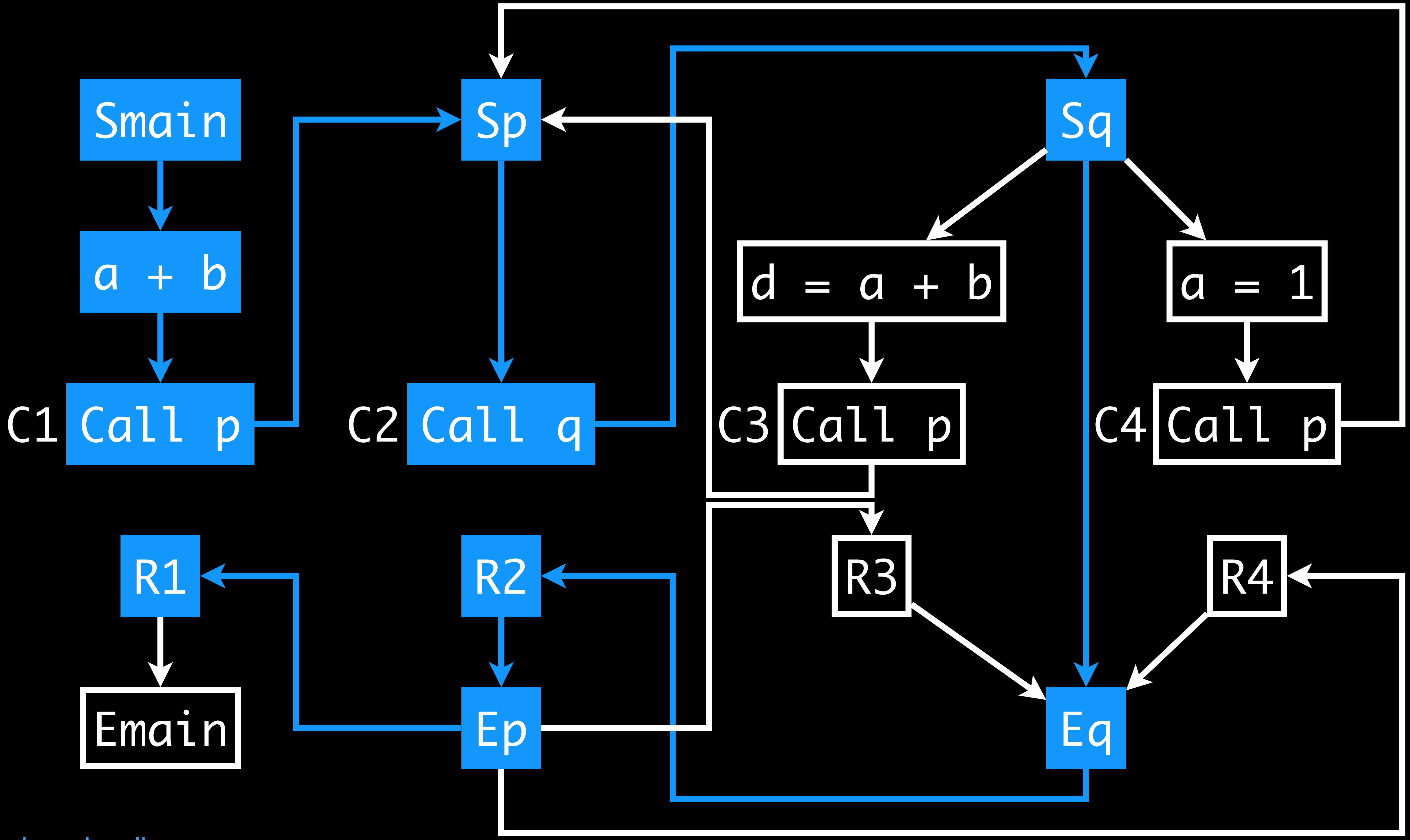

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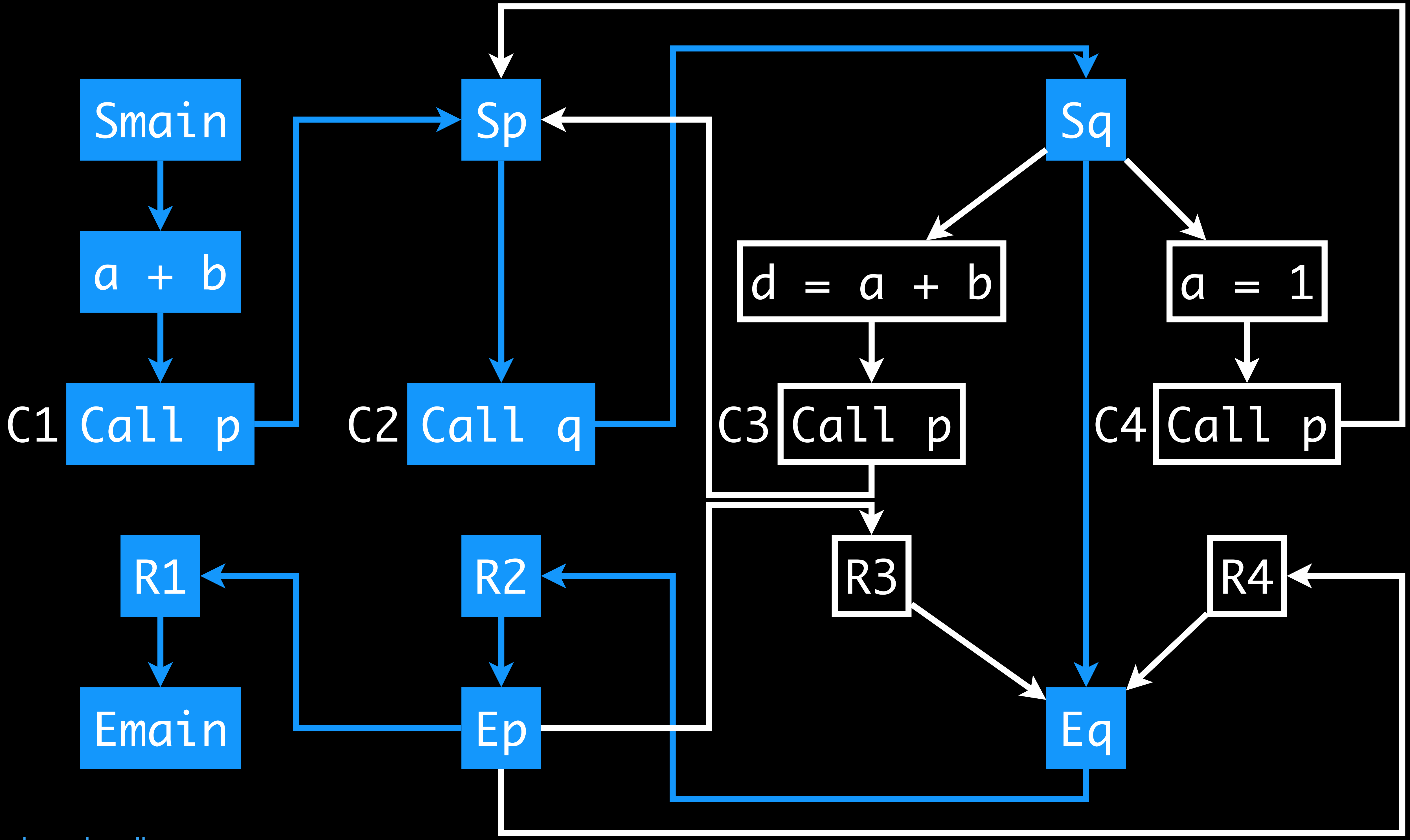

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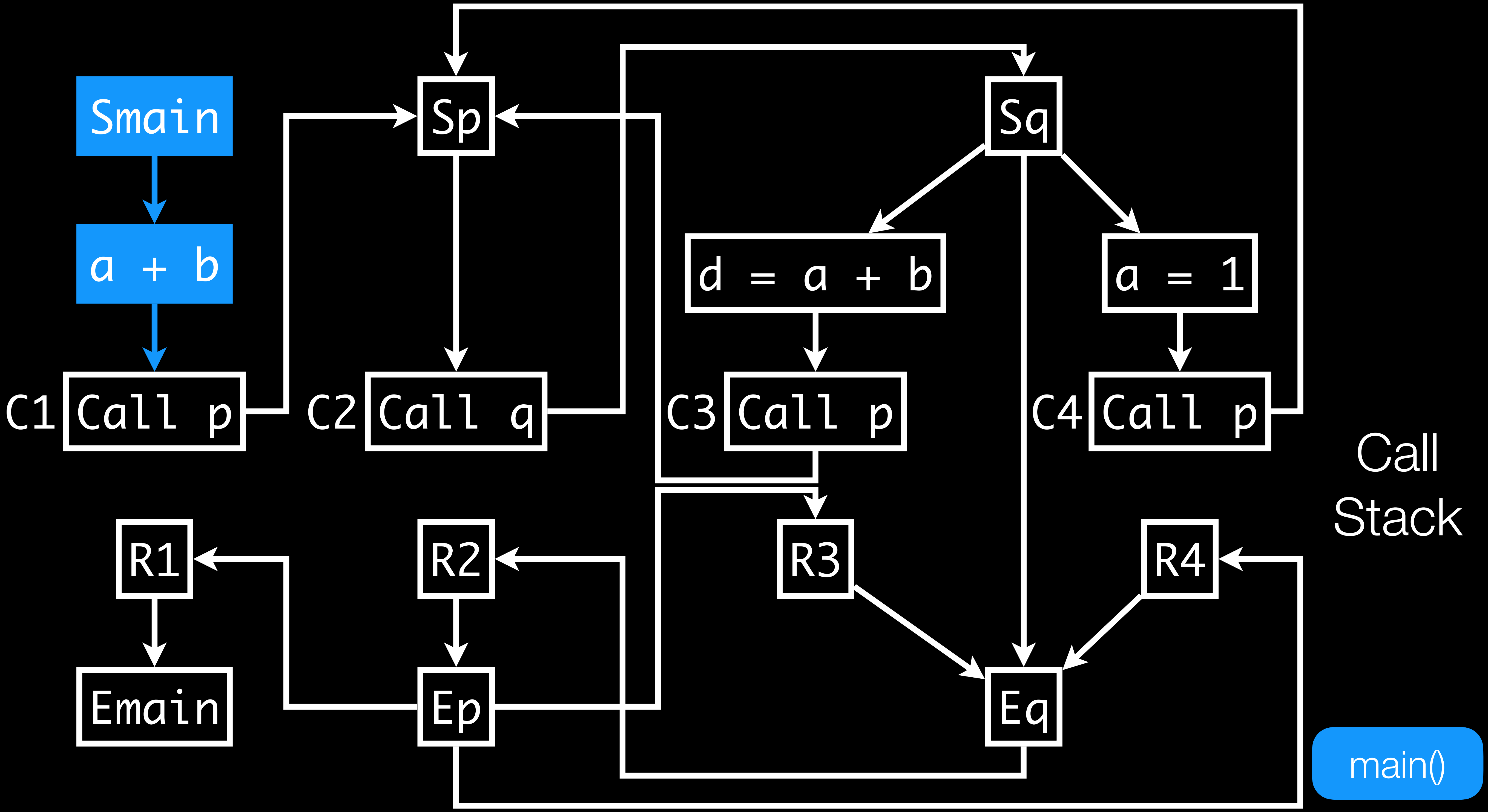

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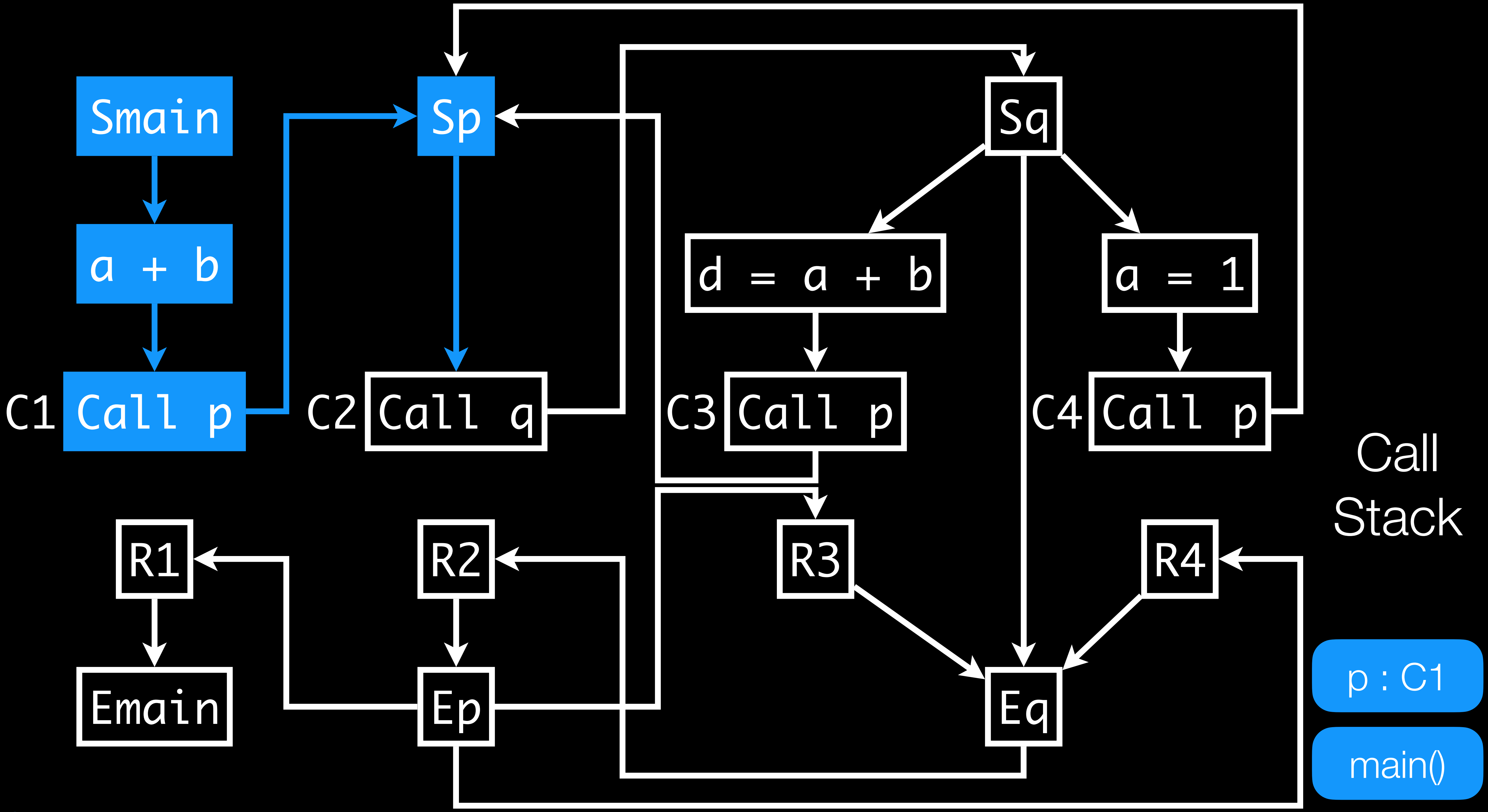

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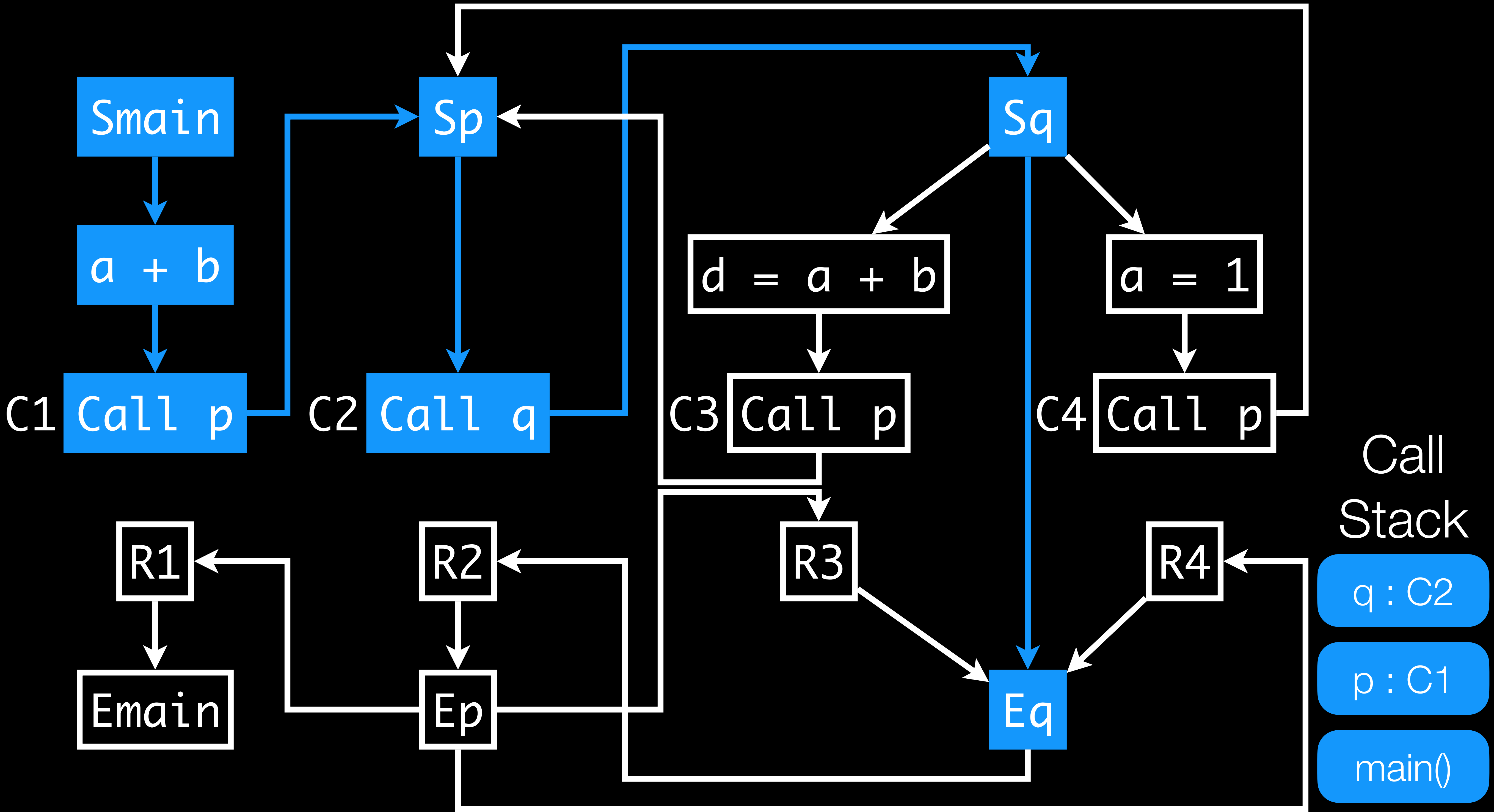

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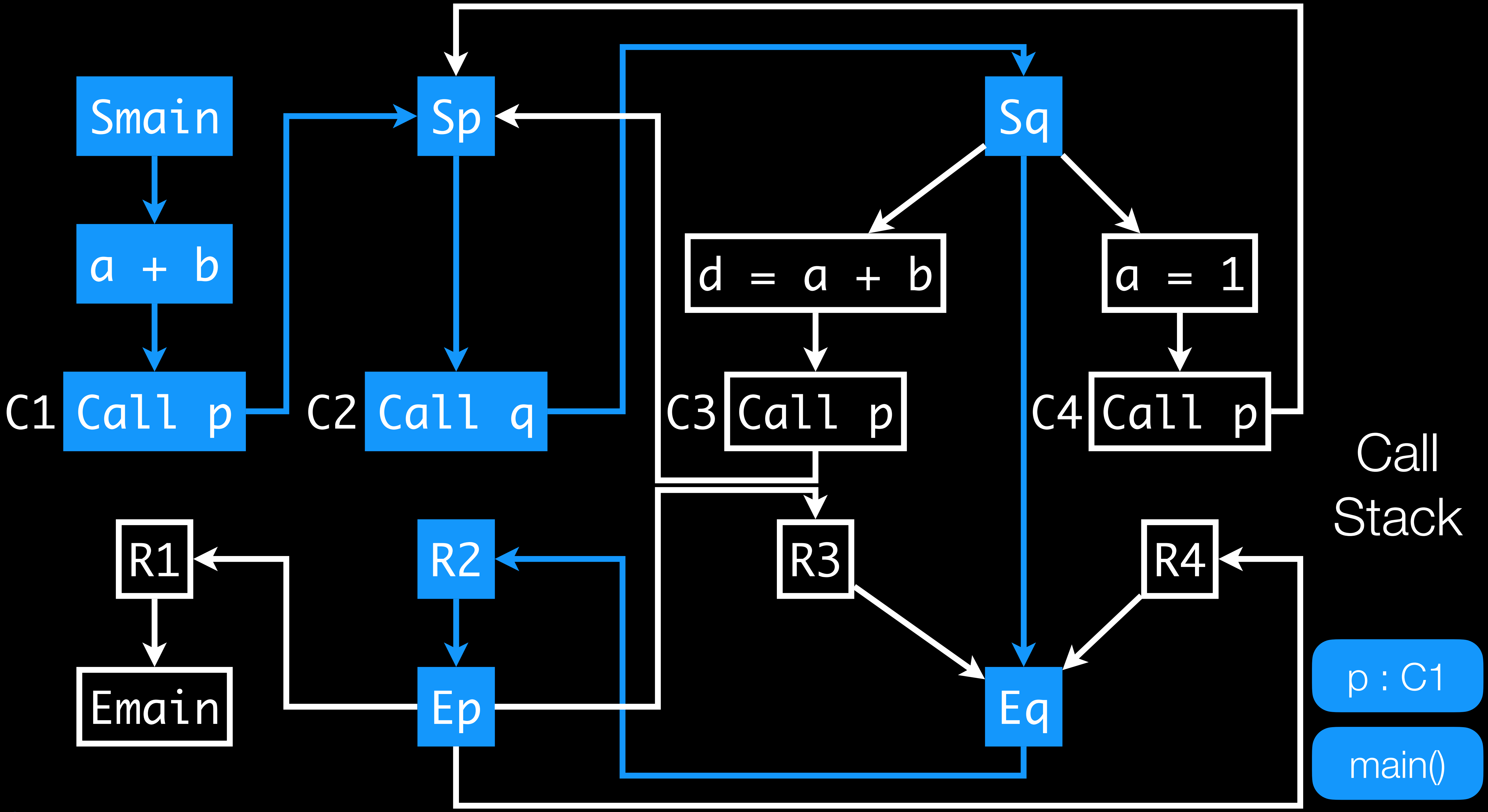

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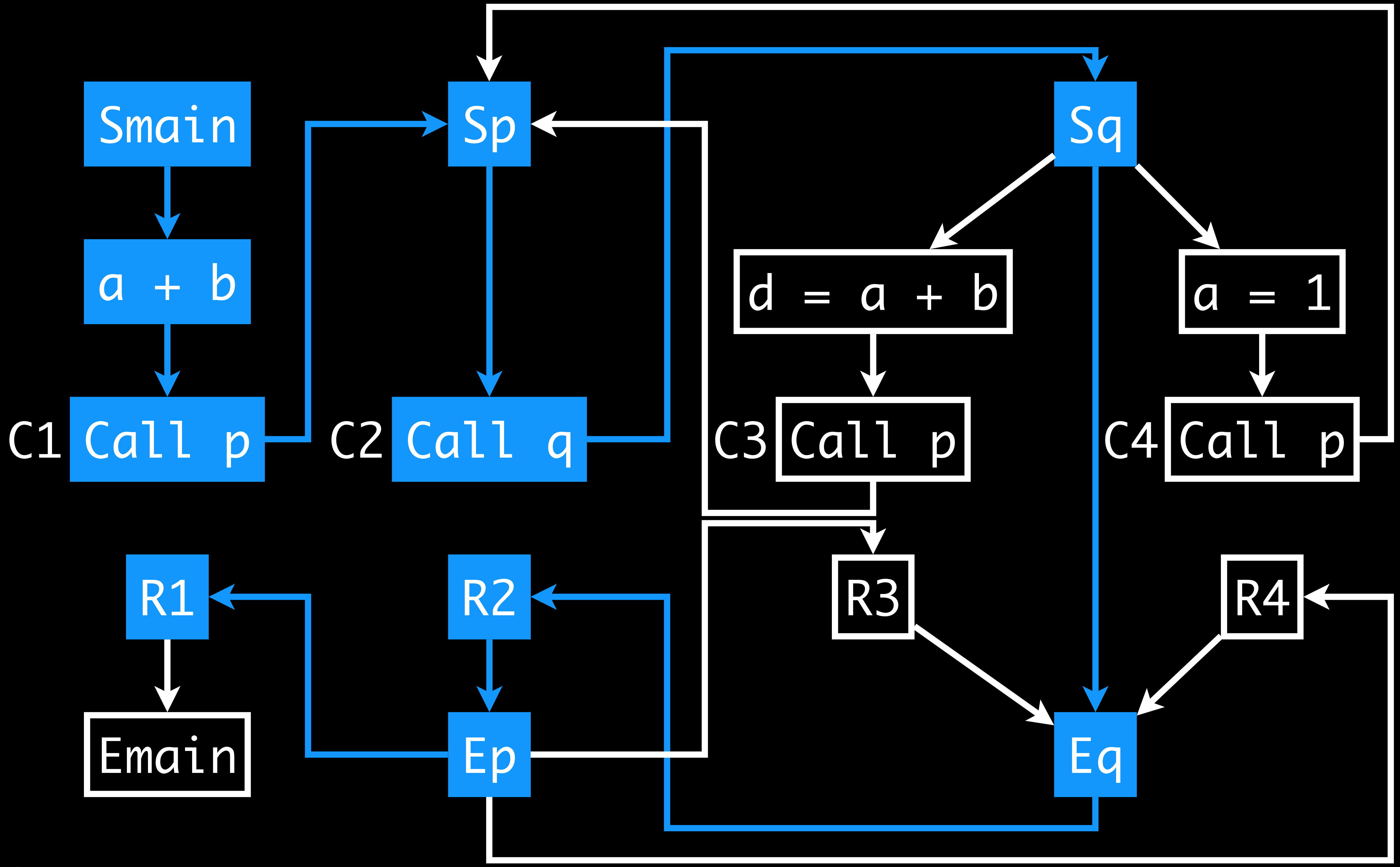
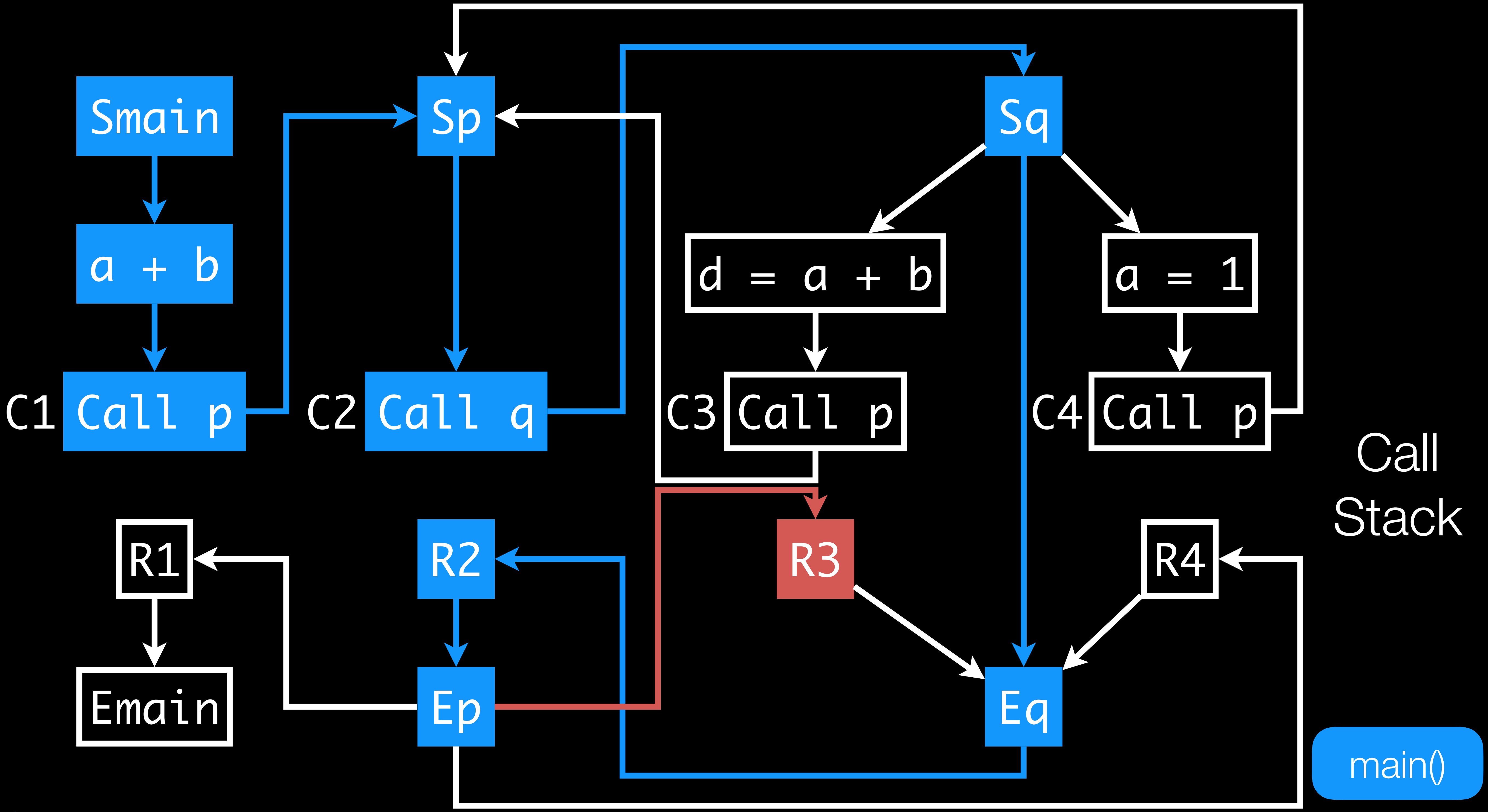


Call Stack

main()

## Valid/Realizable Path



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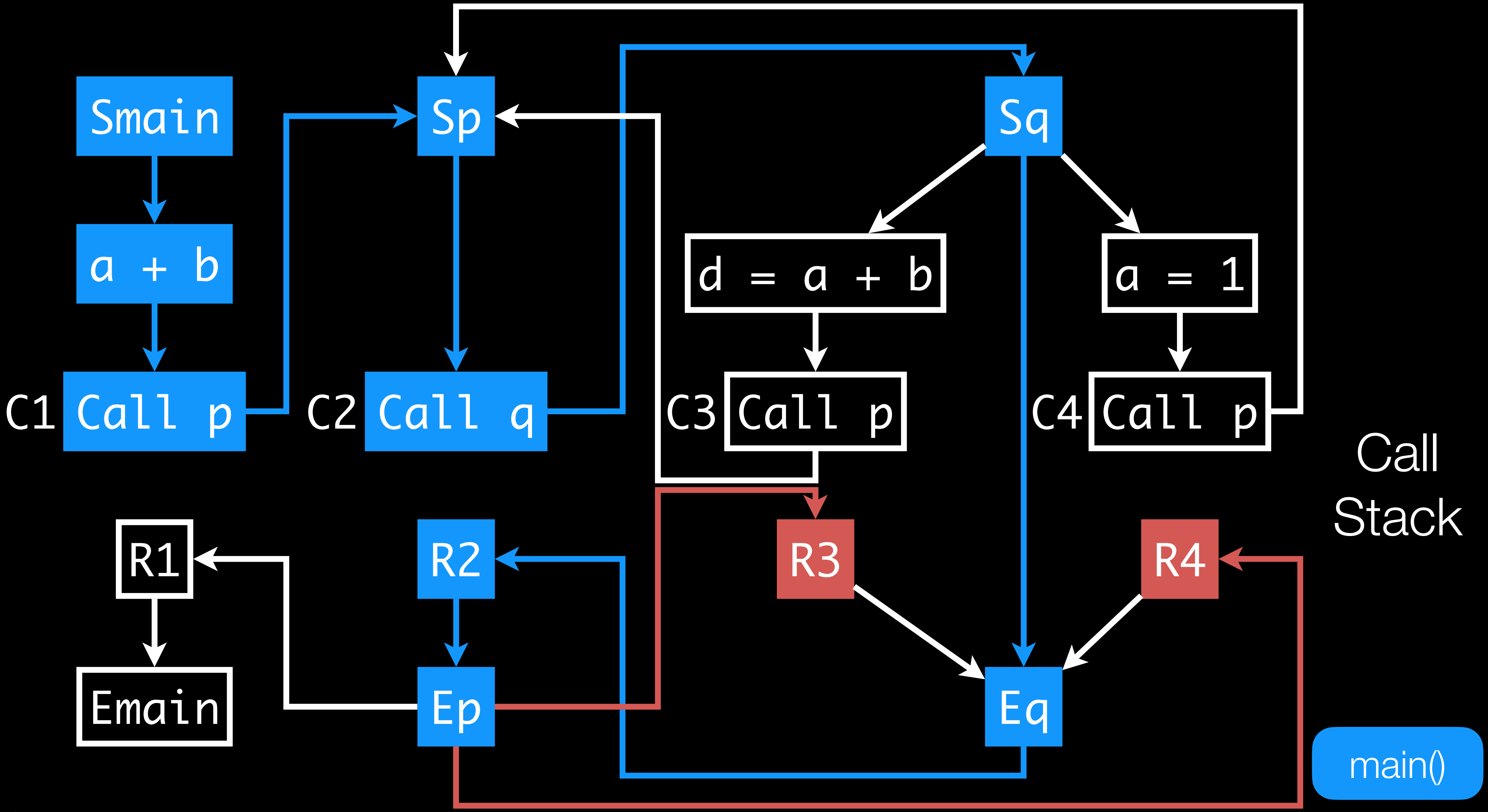

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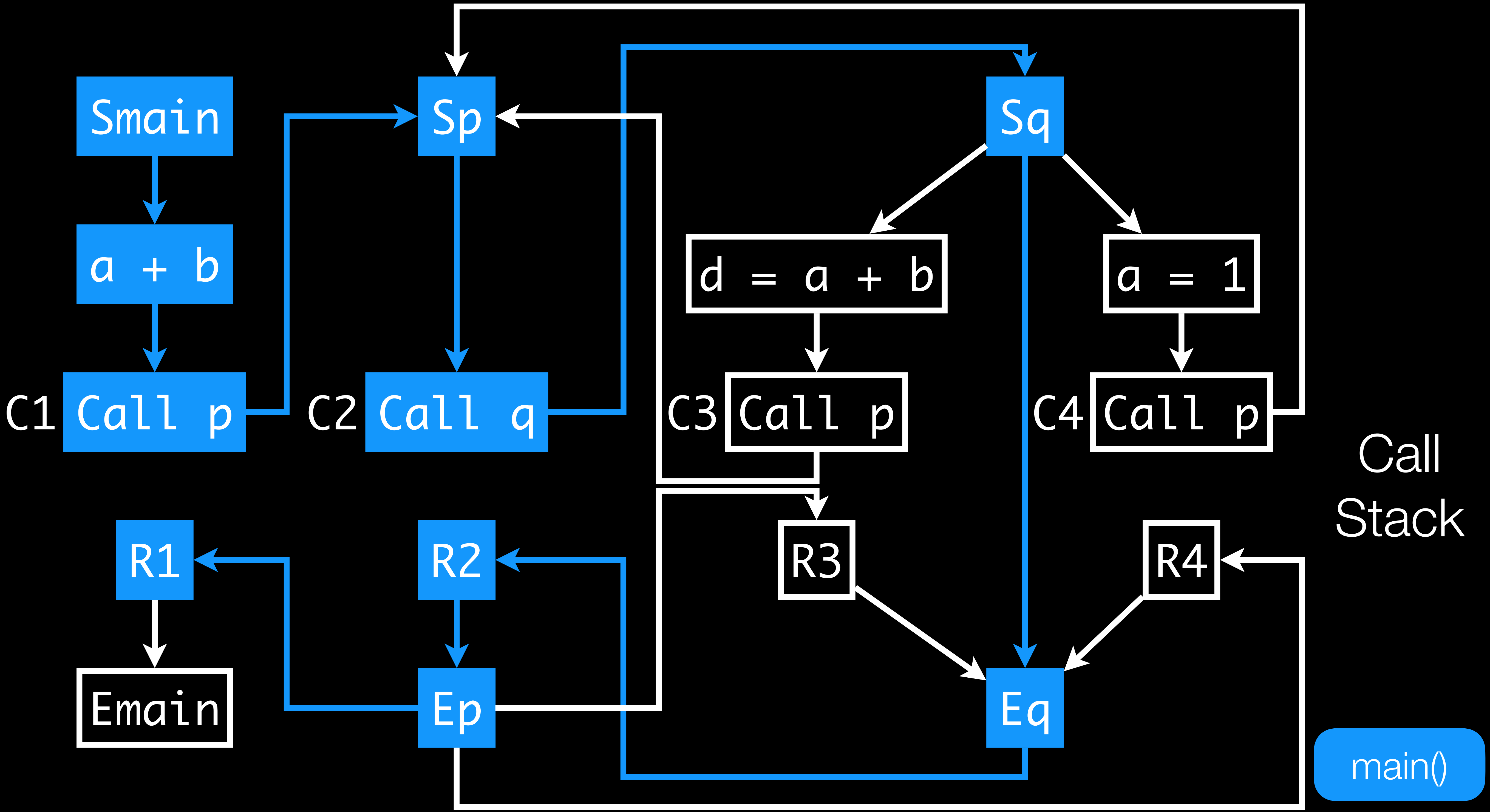

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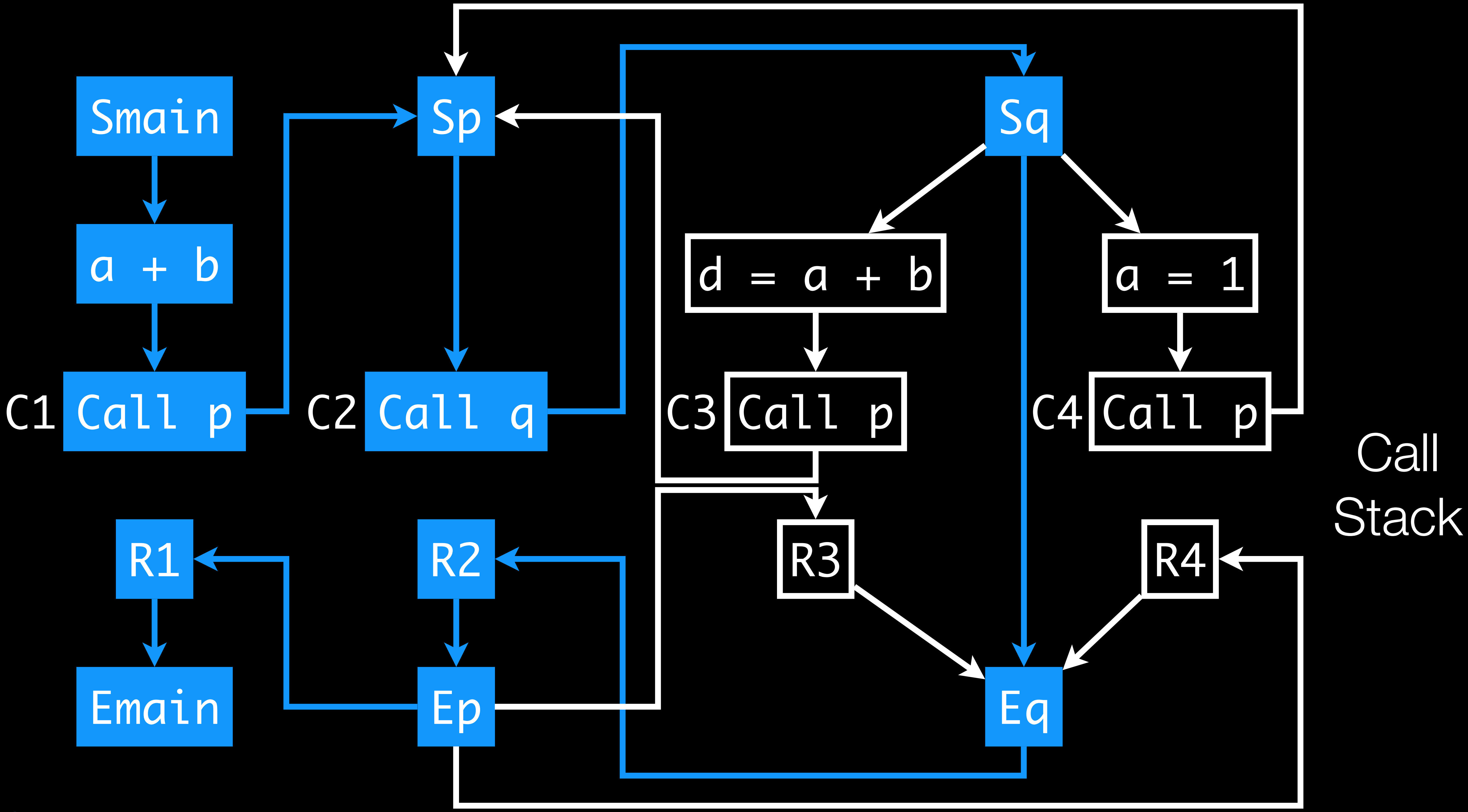
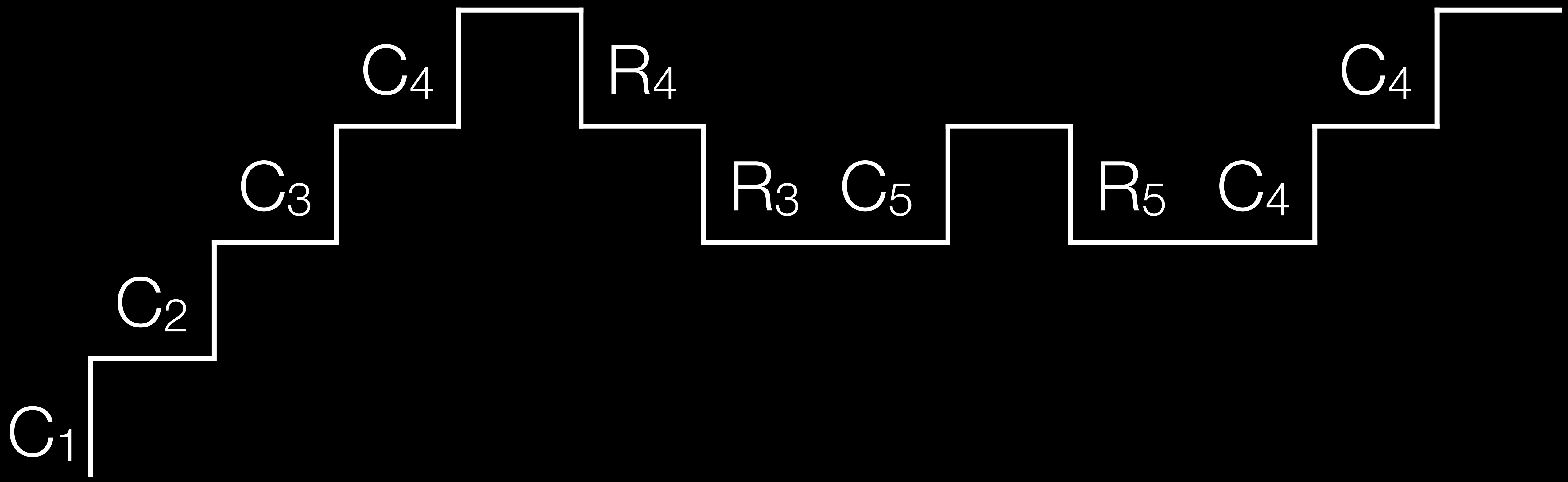


## Recognizing Invalid Paths
## Staircase of Calls & Returns



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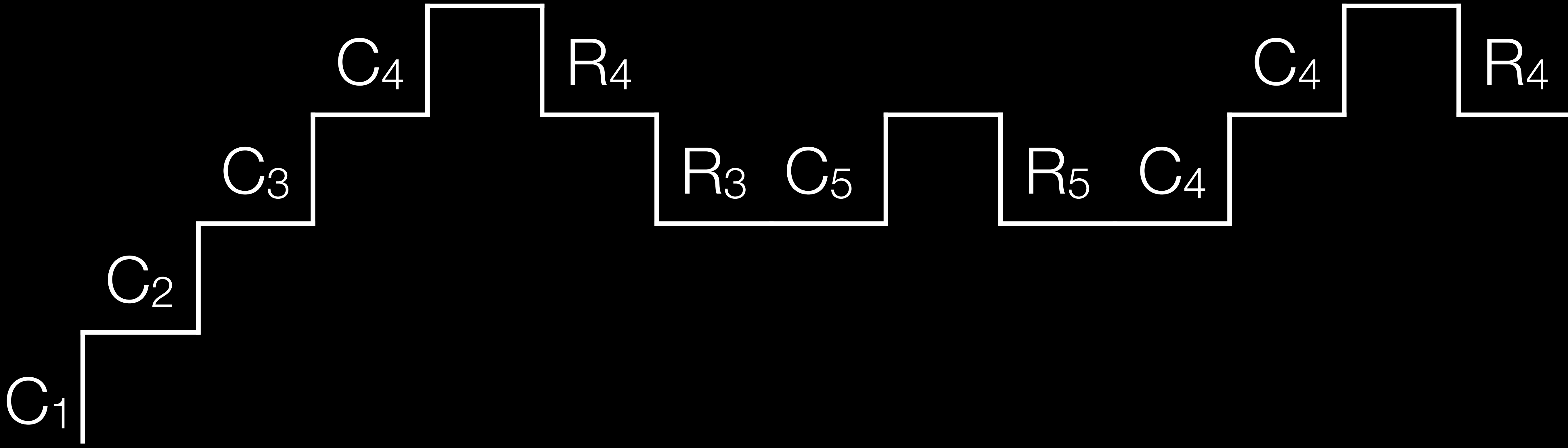
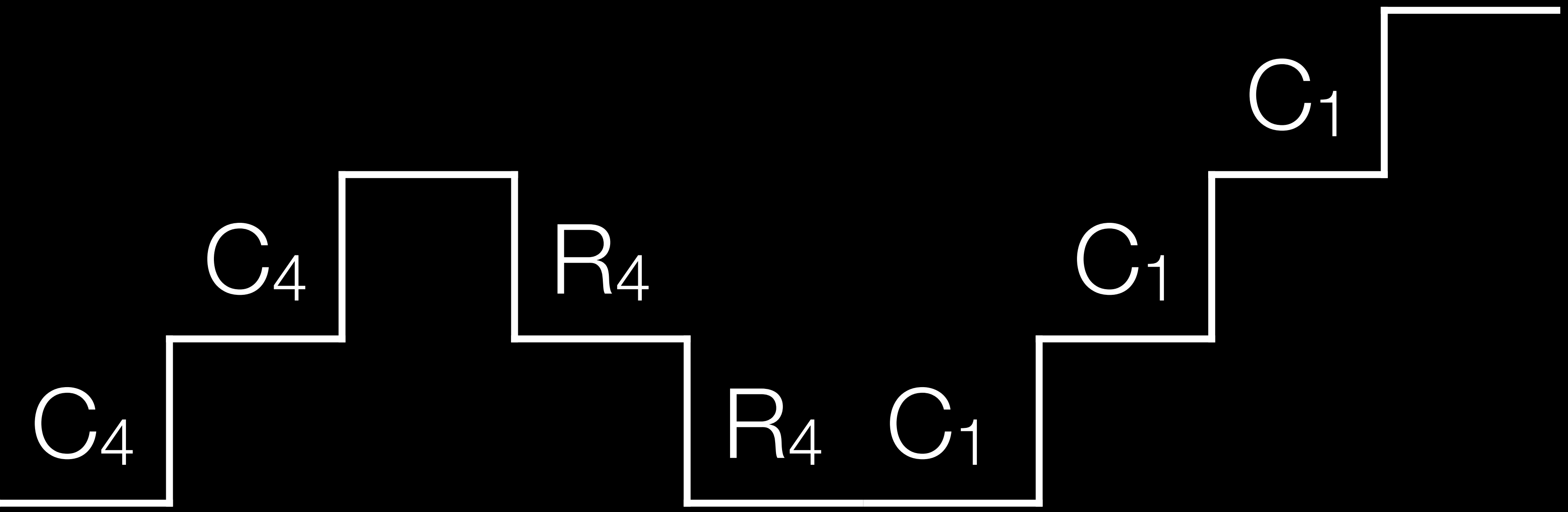
## Staircase of Calls & Returns



## Recognizing Invalid Paths
## Staircase of Calls & Returns



Every descending step must match
a corresponding ascending step

2 problems with that!

## Problem # 1: Recursion

u

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$$\begin{tikzcd}
u \arrow[dr, bend right] & \\
& S_p
\end{tikzcd}$$

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$$\begin{tikzcd}
u \arrow[dr, bend right] & & \\
& S_p \arrow[dr, bend right] & \\
& & S_i
\end{tikzcd}$$

## Problem # 1: Recursion

$$\begin{tikzcd}
u \arrow[dr, bend right] & & \\
& S_p \arrow[dr, bend right] & \\
& & S_i \arrow[r, bend right] & S_q
\end{tikzcd}$$

## Problem # 1: Recursion

$$\begin{tikzcd}
u \arrow[dr, bend right] & & & & \\
& S_p \arrow[dr, bend right] & & & S_j \\
& & S_i \arrow[r, bend right] & S_q \arrow[ur, bend right] &
\end{tikzcd}$$

## Problem # 1: Recursion

$$\begin{tikzcd}
u \arrow[ddr, bend right] & & & & \\
& & & S_r & \\
& S_p \arrow[dr, bend right] & & & S_j \arrow[ul, bend right] \\
& & S_i \arrow[r, bend right] & S_q \arrow[ur, bend right] &
\end{tikzcd}$$

## Problem # 1: Recursion

$$\begin{tikzcd}
u \arrow[dd, bend right] & & & \\
& S_k & S_r \arrow[l, bend right] & \\
S_p \arrow[dr, bend right] & & & S_j \arrow[ul, bend right] \\
& S_i \arrow[r, bend right] & S_q \arrow[ur, bend right] &
\end{tikzcd}$$

## Problem # 1: Recursion

$$\begin{tikzcd}
u \arrow[dd, bend right] & & & \\
& S_k \arrow[dl, bend right] & S_r \arrow[l, bend right] & \\
S_p \arrow[dr, bend right] & & & S_j \arrow[ul, bend right] \\
& S_i \arrow[r, bend right] & S_q \arrow[ur, bend right] &
\end{tikzcd}$$

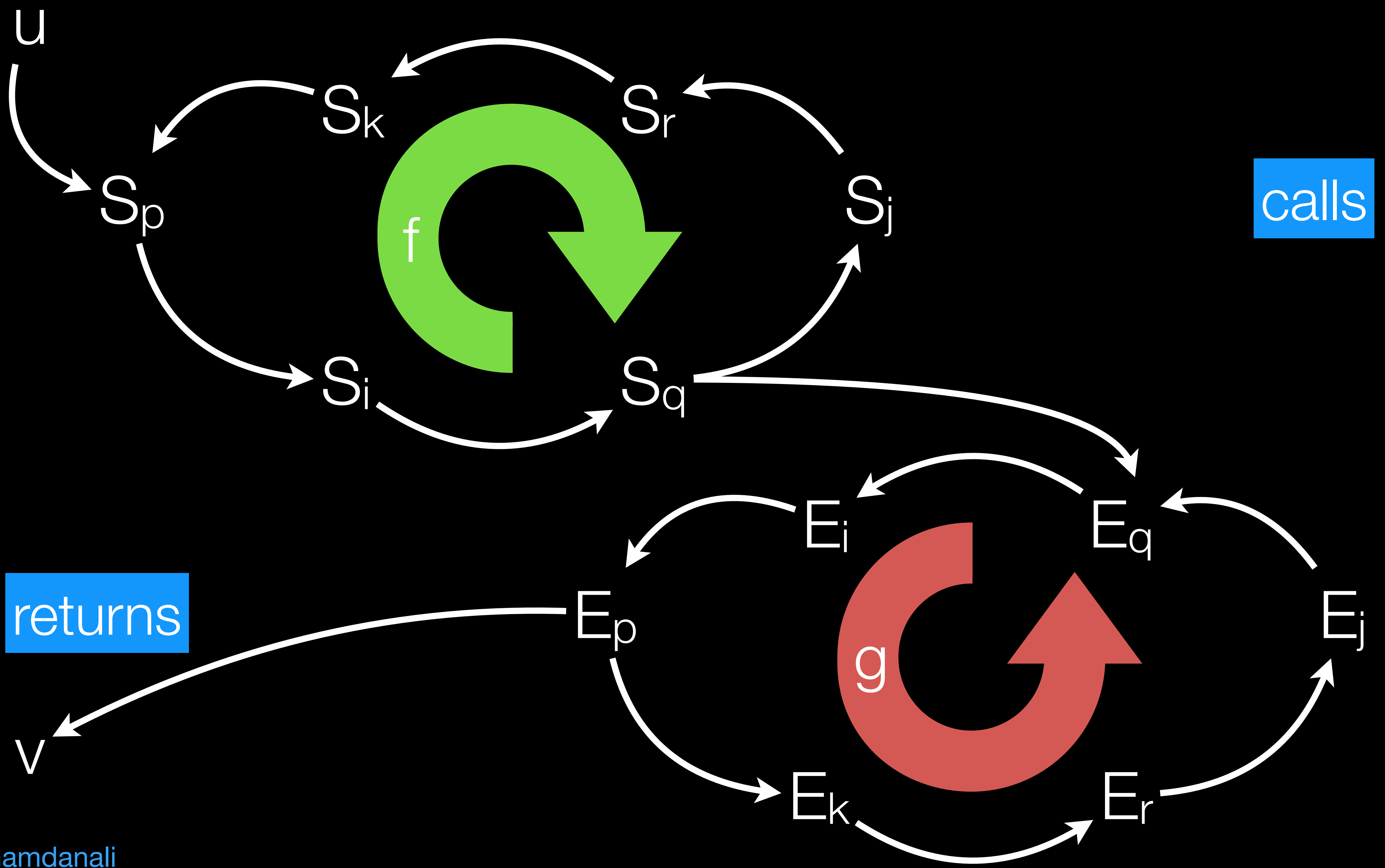
calls

## Problem # 1: Recursion

$$\begin{tikzcd}
u \arrow[dd, bend right] & & & & \\
& S_k \arrow[dl, bend right] & S_r \arrow[l, bend right] & & \\
S_p \arrow[dr, bend right] & & & S_j \arrow[ul, bend right] & \\
& S_i \arrow[r, bend right] & S_q \arrow[ur, bend right] \arrow[drr, bend left] & & \\
& & & & E_q
\end{tikzcd}$$

calls

# Problem # 1: Recursion



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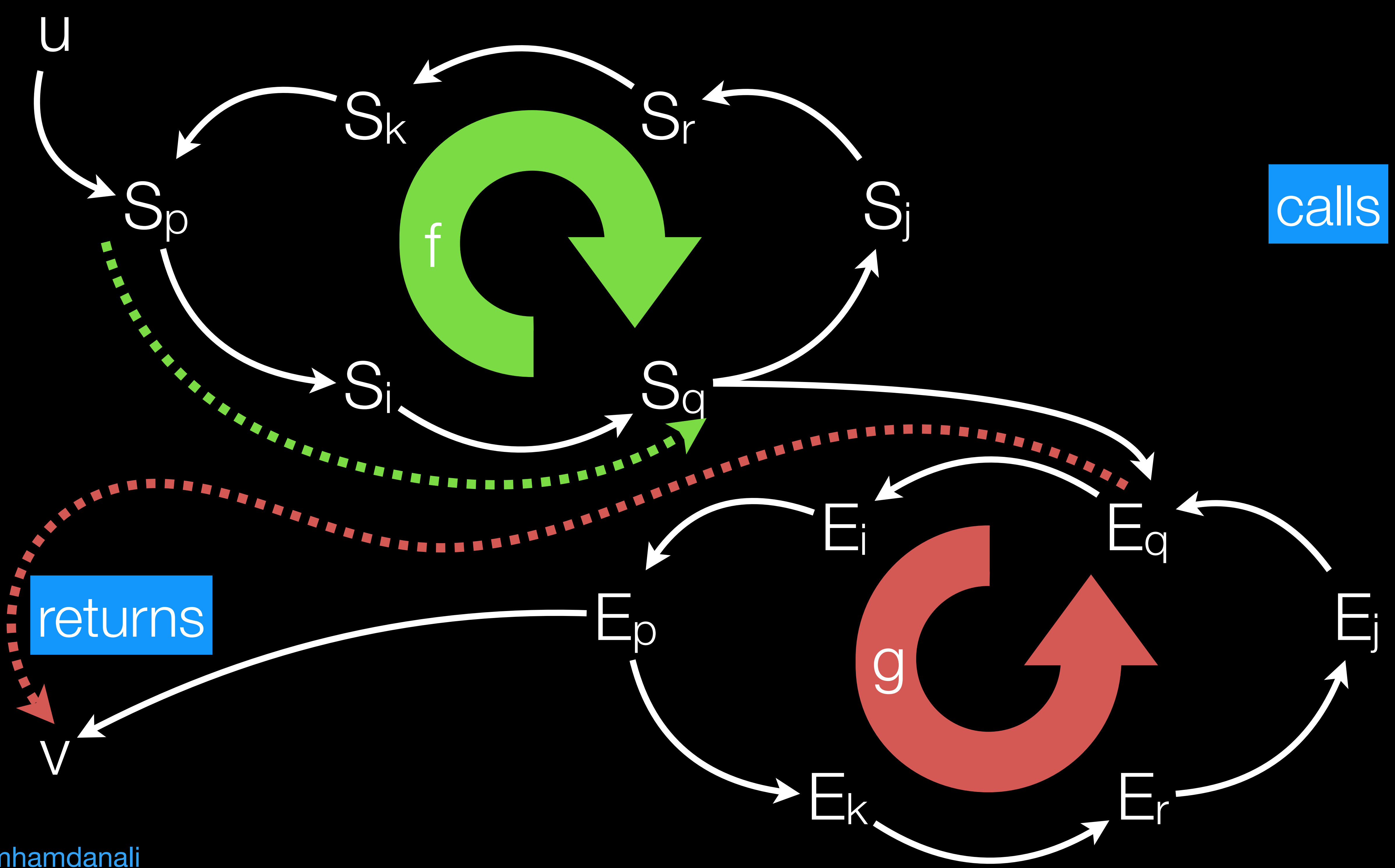
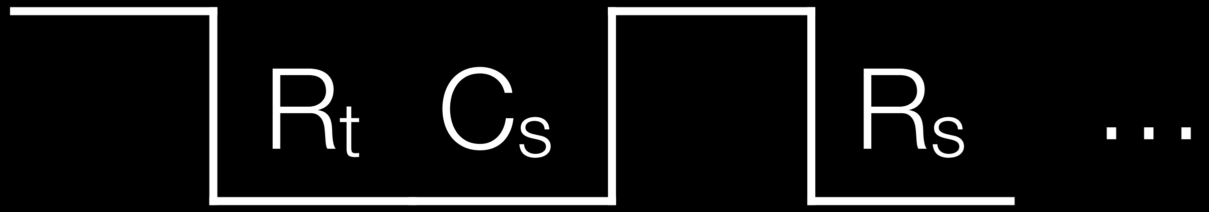


## Problem # 2: Demand-Driven Analysis

```
main() {
   s = secret();
   foo(s);
   t = “123”;
   foo(t);
}
foo(v) { leak(v); }
```

assume we search from `foo(v)` backwards to find possible inputs



here: “unbalanced return” without a call must return to all possible callers

## Solution:
## Context-Sensitive Analysis

## Context-Sensitive Analysis

- Analyze the same method, depending on the context of the current call to that method

## Context-Sensitive Analysis

- Considerations:
  - How to distinguish different contexts?
  - Which contexts can be merged?

## Types of Context

- A call string that encodes the methods/call sites on the current call stack
- A value context that uses the input domain values as context
- An object context that uses the currently executing object as context
- and more…

## Important Language Features

## Recursion

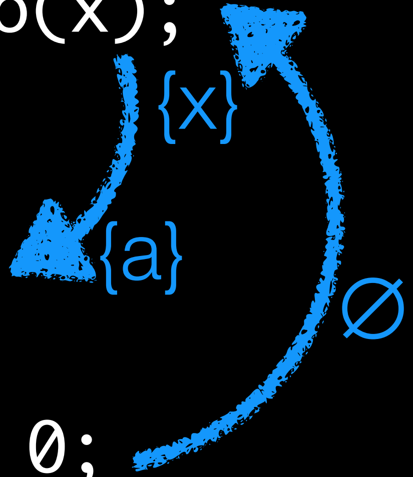
- Must bound computation and contexts
- Often uses flow-insensitive analysis to over-approximate

## Parameters/Return Values

- Must map actuals to formals and vice versa
- Don't propagate too much info:
  - at a call: propagate only the facts relevant to that callee
  - at a return: propagate only the facts relevant to the caller
- Question: what to do with static fields?

```
main(){
    x = source();
    y = x;
    z = foo(x);
}

foo(a) {
    b = a;
    return 0;
}
```



## Aliasing

aliases might be created by callers and callees

```
main(){
   a.f.g = source();
   foo(a,b);
   leak(b.f.g);
}

foo(x,y) {
   y.f=x.f;
}
```

## Virtual Dispatch

- Multiple possible call targets per call site
- Consider them all!
  - “may” or “must” analysis?
  - similar to intra-procedural branches at if-then-else constructs (combine)

## Threads

- Intra-procedural analyses are typically sound despite multi-threaded execution
- Inter-procedural analyses are typically *un*sound if flow-sensitive!
- Flow-insensitive analyses not impacted by multi-threading
- Effective modelling of synchronization constructs is a big open research problem!

## Library Dependencies

- Typically analyze an application with its dependencies
- But what about native code?
- Often need to resort to hand-crafted summaries
- Possible way out: summarization (e.g., Averroes)

## Recap

- Context-sensitivity analyzes a method multiple times, once per context
- Challenges: Recursion, parameters, aliasing, virtual dispatch, threads, libraries

## Next

- Context sensitivity